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JCAA/JG-PP Lead-Free Solder Project

Joint Test Report

Executive Summary

July 14, 2006

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This document is intended to summarize the test data generated from the Joint Council on Aging Aircraft (JCAA)/ Joint Group on Pollution Prevention (JG-PP) Lead-Free Solder Project.

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This project was internationally recognized in 2005 as the recipient of the Lead-Free Solder Award, 2005 by SolderTec Global in recognition of the group's collaboration towards the understanding of how lead-free solders perform under harsh environments.

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1 Introduction

The objective of the project was to compare relative reliability of lead-free (Pb-free) and tin-lead (SnPb) solder joints under different environmental testing conditions.

Solder materials are used in assemblies within many electronic platforms used by the aerospace and defense industry. Therefore, any change in soldering technology will have major implications for military and aerospace operations. Such a challenge is now facing agencies such as United States (U.S.) Department of Defense (DoD) and the National Aeronautics and Space Administration (NASA) in the commercial industry's push towards Pb-free solder. This push is fueled by European legislative actions on the use of lead and, increasingly, by commercial and marketing activities outside the U.S.

While Pb-free solders are purported to reduce environmental and health risks, these new solders present certain technical risks. Of prime concern is that the reliability of most Pb-free solders has not been established for high-reliability applications and the adverse environments to which military and space platforms are subjected.

It has been estimated that aerospace applications command less than 1% of the total electronics market. As a result, high-reliability users have little control over the direction of the overall industry. Pb-free electronics will be finding their way into the inventory of aerospace and defense assembly processes under government acquisition reform initiatives. These actions will result in increased risks associated with manufacturing and subsequent repair of aerospace and defense electronic systems. The net result is that military and aerospace users are now in a position where they need hard data to help them understand the extent to which Pb-free solders may perform differently than SnPb solder.

To address the need for comprehensive test data on the reliability of Pb-free solders, the U.S. DoD's Joint Group on Pollution Prevention (JG-PP) partnered with the DoD's Joint Council on Aging Aircraft (JCAA) to generate reliability data for circuit cards manufactured and reworked with Pb-free solders and subjected to rigorous environmental testing. Beginning in 2001, a team of technical representatives from the DoD, NASA, U.S. and European aerospace and defense original equipment manufacturers (OEMs), component suppliers, and solder suppliers began to identify Pb-free solder alloys for testing and which tests should be conducted that best represent the environments experienced by aerospace and military high performance electronics systems.

2 Materials

2.1 Materials

Project technical representatives selected three Pb-free solder alloys for testing:

- 95.5Sn3.9Ag0.6Cu (SAC)
- 92.3Sn3.4Ag1.0Cu3.3Bi (SACB)
- 99.3Sn0.7Cu, Ni-stabilized (SnCu)

Sn = Tin Ag = Silver Cu = Copper Bi = Bismuth Ni = Nickel

Selection criteria of prime importance included commercial availability, industry trends, and past reliability testing performance.

Eutectic 63Sn37Pb (SnPb) alloy was used as the control for all testing. The SAC alloy was used for reflow, wave and hand soldering. The SACB was used for reflow and hand soldering. Stabilized SnCu was used for wave and hand soldering.

The recommended flux of each solder manufacturer was used. A rosin-based (ROL1 and RMA) flux vehicle was used for Pb-free reflow. A volatile organic compound (VOC)-free no clean flux was used for Pb-free wave soldering. The project technical representatives chose to process all test vehicles in fully cleaned mode, the test vehicles represent both standard rosin and low residue soldering processes found in numerous Class 3 OEM processes.

2.2 Test Vehicle Design

The test vehicle included a variety of plated through hole (PTH) and surface mount technology (SMT) components. All components were dummy parts containing simulated die with the component pins internally daisy-chained. The test vehicle was designed with daisy-chained pads that are complementary to the daisy chain in the components, except for the chip capacitors. The solder joints on each component type act as part of a continuous electrical pathway. This was done to allow use of an event detector to monitor the solder joints during testing. A breakaway coupon containing chip capacitors and resistors was designed into the vehicle to allow periodic removal of components for analysis during thermal cycle testing. The size of the test vehicle was 14.5 X 9 X 0.09 inches with six 0.5-ounce copper layers.

Component issues required that a secondary "Hybrid" test vehicle be designed and assembled to accommodate the hybrid and chip scale packages (CSP) that were omitted from the primary test vehicle. The hybrids required a recessed area on the printed circuit board.

The Electrochemical Migration Resistance (EMR) and Surface Insulation Resistance (SIR) Tests used standard test boards as test vehicles. IPC-B-25A boards with D-comb pattern were used for EMR and IPC-B-24 boards were used for SIR.

2.3 Components

The components were selected to represent package styles and lead types commonly found on legacy aerospace and defense systems as well as on new systems. Plated through-hole and surface mount technologies were selected. The component types used on the test vehicles were: ceramic leadless chip carriers (CLCC-20); plastic leaded chip carriers (PLCC); thin small outline packages (TSOP-50); thin quad flat packs with both 144 and 208 pins (TQFP-144 and TQFP-

208); plastic ball grid arrays (BGA-225); plastic dual-in-line packages (PDIP-20); CSP; hybrid; 0402, 0805, and 1206 surface mount ceramic capacitors; and 1206 surface mount resistors.

The CLCC-20 and Alloy 42 TSOP-50 component types were selected due to their recognized poor solder joint reliability under thermal cycling conditions. The PDIP-20 components were selected to represent plated through hole technology. The PLCCs, TQFP-144s, TQFP-208s, BGA-225s, and capacitor/resistors were selected to represent surface mount technology. CSPs were selected because they represent one of the newest surface mount technologies being used on printed wiring assemblies today. Hybrid components are one of the oldest technologies on the test vehicle and can be found on Class 3 printed wiring assemblies, e.g. those used on the F-15 fighter aircraft.

Six component finishes; SnPb, SAC, SACB, nickel-palladium-gold (NiPdAu), SnCu, and Sn were used, though not for every component type. Six of the component types (CLCC, TSOP, BGA, PDIP, Hybrids, CSP) had multiple surface finishes, while the other components (PLCC, TQFPs, capacitors, and resistor) had a single finish, as shown in Table 1. The CLCC-20s were procured with a either a SnPb or a gold component finish. The gold CLCC-20s were sent to Corfin Industries for solder dipping with SAC and SACB.

Table 1 Component Types and Finishes

Component Type	Component Finish
CLCC-20	SnPb
	SAC
	SACB
PLCC-20	Sn
TSOP-50	SnPb
	SnCu
TQFP-144	Sn
TQFP-208	NiPdAu
BGA-225	SnPb
	SAC
PDIP-20	Sn
	NiPdAu
0402 Capacitors	Sn
0805 Capacitors	Sn
1206 Capacitors	Sn
1206 Resistor	Sn
Hybrids	SnPb
	SAC
	SACB
CSPs	SnPb
	SAC

3 Assembly

BAE Systems (Irving, Texas) performed assembly and rework of the 205 test vehicles following their standard processes and procedures used for manufacturing high-performance electronic circuit card assemblies. Pb-free wave soldering was performed at Vitronics-Soltec (New Hampshire) followed by cleaning at Kyzen (New Hampshire). Certified operators performed the hand soldering and rework operations while certified inspectors performed the inspections. An individual “traveler” accompanied each test vehicle through assembly. Reflow temperature profiles were appropriately adjusted for the Pb-free solder alloy. A detailed description of the SnPb and Pb-free soldering processes is presented in section 3.1 and 3.2 of this JTR.

3.1 Primary Test Vehicle Assembly

Figure 1 is a schematic of the primary test vehicle with each component labeled. Figure 2 is a photograph of the primary test vehicle. Table 2 lists the component types with surface finishes used on the primary test vehicles.

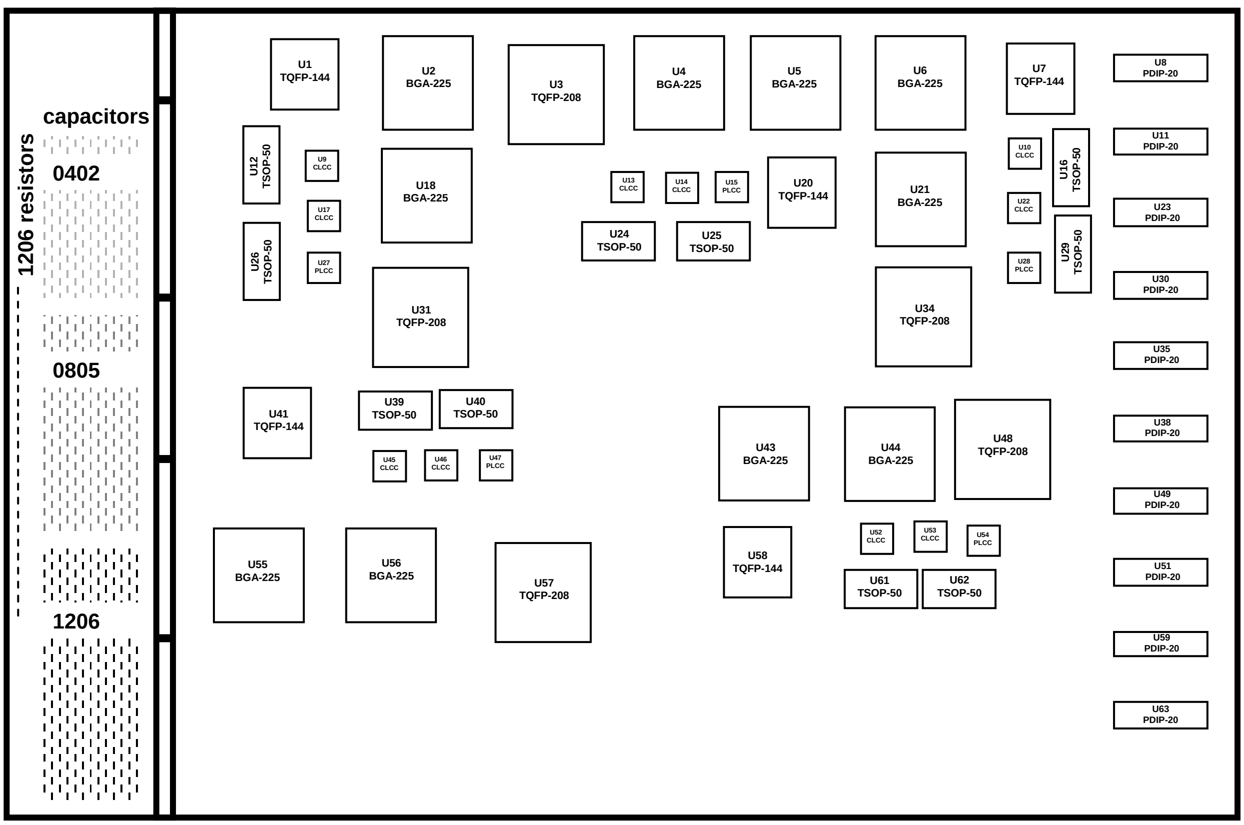

Figure 1 Schematic Diagram of Primary Test Vehicle

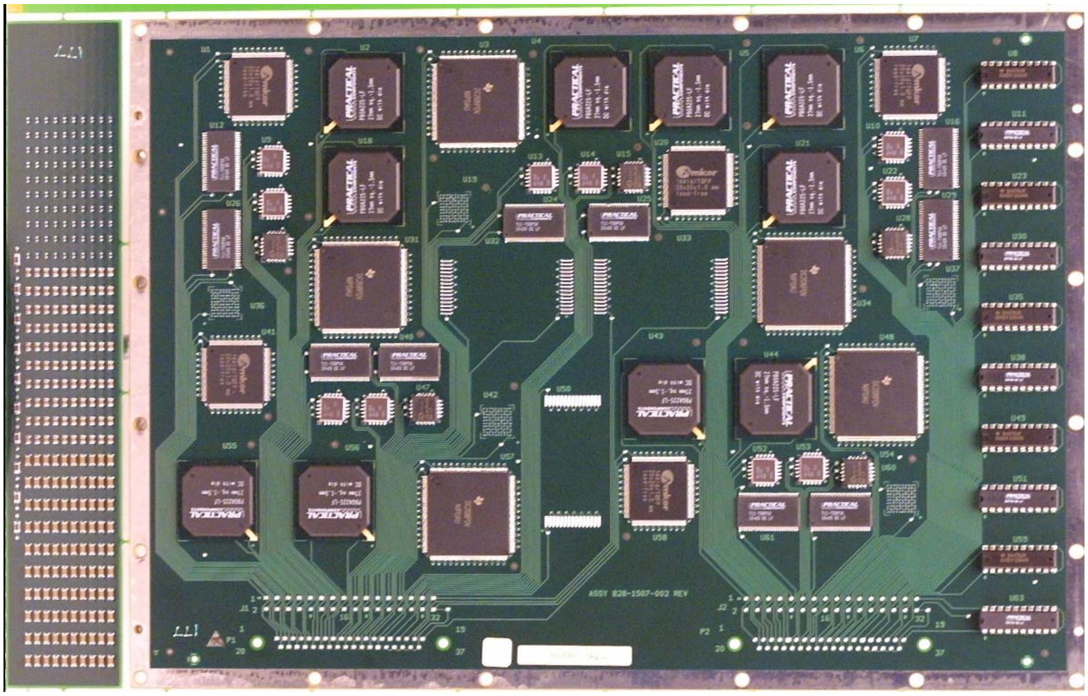

Figure 2 Photograph of Primary Test Vehicle

Table 2 Primary Test Vehicle Component Types and Finishes

Component Type	Component Finish
CLCC-20	SnPb
	SAC
	SACB
PLCC-20	Sn
TSOP-50	SnPb
	SnCu
TQFP-144	Sn
TQFP-208	NiPdAu
BGA-225	SnPb
	SAC
PDIP-20	Sn
	NiPdAu
0402 Capacitors	Sn
0805 Capacitors	Sn
1206 Capacitors	Sn
1206 Resistor	Sn

A total of six types of vehicles were assembled (See Table 3). Three types were referred to as "Manufactured" and the other three types as "Rework" test vehicles. "Manufactured" test vehicles represented printed wiring assemblies that were designed for use in Pb-free soldering processes. The "Manufactured" test vehicles were assembled using immersion silver (Ag) finished glass fiber (GF) laminate (IPC-4101/26) printed circuit boards with a glass transition temperature, T_g, of 170°C. The "Rework" test vehicles represented legacy printed wiring assemblies that were not specifically designed for Pb-free soldering processes but that would be reworked using Pb-free solders. The "Rework" test vehicles were assembled using SnPb Hot Air Solder Leveled (HASL) surface finished glass fiber laminate (IPC-4101/21) printed circuit boards with a T_g of 140°C.

The test vehicles allowed for the evaluation of mixed Pb-free and SnPb alloys. These combinations included SAC BGA-225's and Pb-free finished components soldered using a SnPb thermal profile and SnPb solder. In addition, the test vehicles include SnPb BGA-225s and SnPb surface finished CLCC-20s and TSOP-50s soldered using a Pb-free thermal profile and Pb-free solder.

Table 3 JCAA/JG-PP Test Vehicle Types

Type	Printed Circuit Board	Reflow Solder	Wave Solder
"Manufactured" Control	T_g~170°C, Immersion Ag	SnPb	SnPb
"Manufactured" SAC	T_g~170°C, Immersion Ag	SAC	SAC
"Manufactured" SACB	T_g~170°C, Immersion Ag	SACB	SnCu
"Rework" Control	T_g~140°C, SnPb HASL	SnPb*	SnPb*
"Rework" SAC	T_g~140°C, SnPb HASL	SnPb*	SnPb*
"Rework" SACB	T_g~140°C, SnPb HASL	SnPb*	SnPb*

SnPb* = before rework was performed

3.2 "Hybrid" Test Vehicle Assembly

The "Hybrid" test vehicles were assembled to yield the three "Manufactured" types (see Table 3) using the hybrids and CSP components. The components and their finishes are shown in Table 4. The printed circuit board was designed for the placement of the hybrids while keeping the same circuit board materials and metallurgies as the primary test vehicle. In addition, the assembly of the "Hybrid" test vehicle used the same SnPb and Pb-free solders and processes as the primary test vehicles. No wave soldering was performed. A photograph of the "Hybrid" test vehicle is shown in Figure 3.

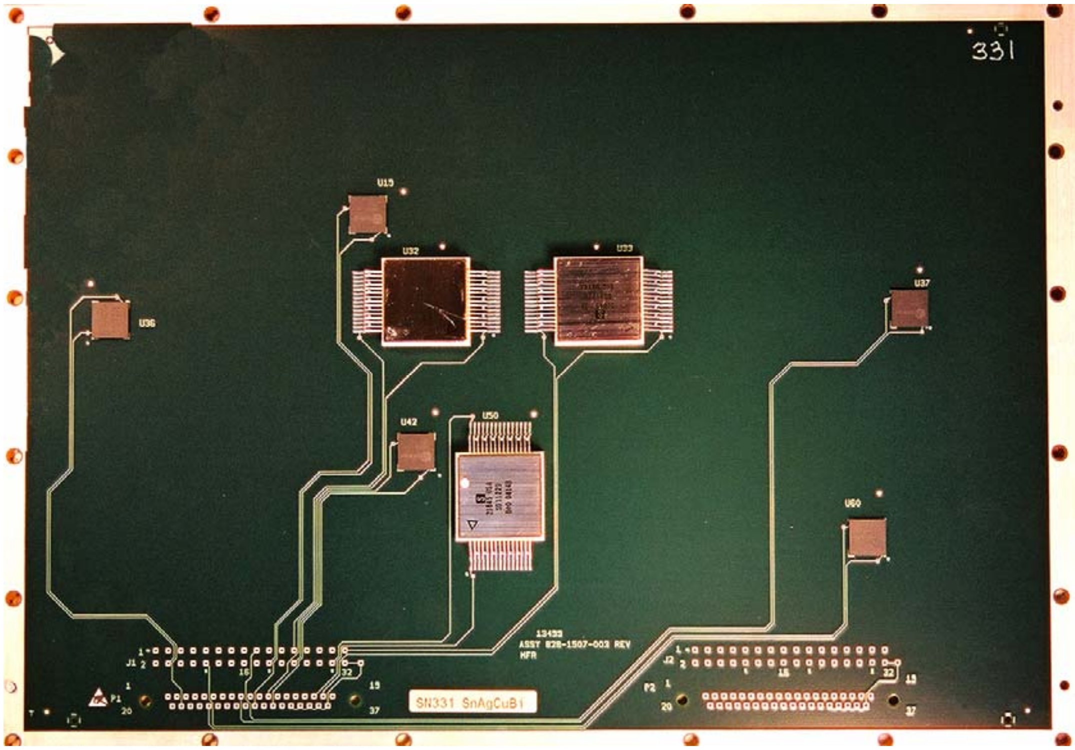

Figure 3 "Hybrid" Test Vehicle

Table 4 "Hybrid" Component Types and Finishes

Component Type	Component Finish
Hybrids Part # 934266-501B	SnPb
	SAC
	SACB
CSPs Part # A-CABGA100-.8mm-10mm-DC	SnPb
	SAC

3.3 Chemical Analysis of Solder Joints

To assess the compositional make-up of the solder joints, chemical analysis of the soldered assemblies was conducted. The method used for analysis was Inductive Coupled Plasma (ICP) method, which provides an accurate analysis of the solder composition.

Table 5 Chemical Analysis of Solder Joints

Component	Ref. Des.	Test Vehicle	Reworked?	Component Finish	Board Finish	Solder	%Ag	%Cu	%Pb	%Sn	%Bi	%Au
CLCC	U9	80	no	SnPb	Ag	Sn3.9Ag0.6Cu	2.5	0.72	16.48	80.04	0.05	0.21
CLCC	U9	119	no	SnPb	Ag	Sn3.4Ag1.0Cu3.3Bi	2.23	0.82	16.76	78.07	1.94	0.18
CLCC	U9	158	no	Sn3.9Ag0.6Cu	SnPb	SnPb	1.52	0.62	22.72	75.11	0	0.03
CLCC	U9	186	no	Sn3.4Ag1.0Cu3.3Bi	SnPb	SnPb	1.32	0.57	22.93	73.86	1.3	0.02
TSOP	U26	80	no	SnPb	Ag	Sn3.9Ag0.6Cu	3.67	1.12	2.84	92.36	0.01	0
TSOP	U26	119	no	SnPb	Ag	Sn3.4Ag1.0Cu3.3Bi	3.16	1.98	3.05	89.01	2.8	0
TSOP	U12	158	yes	SnCu	Residual SnPb	Sn3.9Ag0.6Cu	3.31	2.12	0.86	93.71	0	0
TSOP	U12	186	yes	SnCu	Residual SnPb	Sn3.4Ag1.0Cu3.3Bi	2.89	1.98	1.06	91.52	2.55	0
BGA	U55	158	no	Sn4.0Ag0.5Cu	SnPb	SnPb	3.42	0.7	4.37	91.33	0	0.18
BGA	U4	158	yes	Sn4.0Ag0.5Cu	Residual SnPb	Flux Only	3.86	0.88	0.31	94.69	0	0.26
BGA	U4	186	yes	Sn4.0Ag0.5Cu	Residual SnPb	Flux Only	3.81	0.99	0.3	94.66	0	0.24
BGA	U18	168	yes	Sn4.0Ag0.5Cu	Residual SnPb	Flux Only	4.11	0.38	1.17	94.34	0	0
PDIP	U59	158	yes	NiPdAu	Residual SnPb	Sn3.9Ag0.6Cu	3.5	0.99	2.98	92.53	0	0
PDIP	U59	186	yes	NiPdAu	Residual SnPb	Sn0.7Cu0.05Ni	0	1.04	0.38	98.58	0	0
QFP-208	U3	158	yes	NiPdAu	Residual SnPb	Sn3.9Ag0.6Cu	3.34	6.63*	1.13	88.89	<0.05	<0.05

4 Test Methods and Results

Project technical representatives identified the engineering, performance, and operational impact (supportability) requirements for printed wiring assemblies, reaching consensus on the tests, procedures and acceptance criteria to be applied. This information was documented in a *Joint Test Protocol (JTP) for Validation of Alternatives to Eutectic Tin-Lead Solders used in Manufacturing and Rework of Printed Wiring Assemblies* (February 14, 2003; Revised April 2004).

Table 6 shows the different tasks of the testing phase of the project, the partnering organization performing the task, the number of test vehicles undergoing each test, and the industry standard on which each test was based.

Table 6 Environmental Exposure Tests

Project Activity	Performer	No. of Test Vehicles			Reference
		Mfg.	Rewk.	Hybrid	
Testing Prep					
PWA Assy. & Rework	BAE SYSTEMS	119	86	42	--
Component Characterization	Rockwell Collins	--	--	--	--
Testing					
Vibration	PHANTOM WORKS	15	15	--	MIL-STD-810F
Thermal Shock	PHANTOM WORKS	15	15	--	MIL-STD-810F
Thermal Cycling: $-20^{o}C$ to $+80^{o}C$	PHANTOM WORKS	15	--	--	IPC-SM-785
Thermal Cycling: $-55^{o}C$ to $+125^{o}C$	Rockwell Collins	15	15	15	IPC-SM-785
Combined Environments Testing	Raytheon	15	15	15	MIL-STD-810F
Mechanical Shock	aci	13	13	--	MIL-STD-810F
Salt Fog	aci	9	--	--	IPC-TM-650
Humidity	aci	9	--	--	IPC-TM-650
Surface Insulation Resistance	BOEING	45 IPC-B-24 boards		--	MIL-STD-810F
Electrochemical Migration Resistance	BOEING	45 IPC-B-25A boards		--	MIL-STD-810F

The acceptance criteria for the Pb-free solder alloys was defined as "better than or equal to" eutectic SnPb solder, in terms of electrical failures. Failure of a Pb-free solder alloy in a specific test should not necessarily disqualify the alloy for all uses. For example, a Pb-free solder that fails vibration testing should not be disqualified for an application in a benign vibration environment.

Within the "Results" sections for combined environments, thermal shock, thermal cycle -20°C to + 80°C and thermal cycle -55 °C +125°C the data results have been placed in "Relative Solder Performance" Tables (Table 14, Table 19, Table 20, Table 23, and Table 26). The tables provide a qualitative comparative summary of the relative performance of the Pb-free solder alloys for the "Manufactured", "Hybrid" and "Rework" test vehicles. All comparisons are based on first failure numbers and on 10% and 63% failure numbers derived from a two-parameter Weibull analysis of the test data. Mechanical shock and vibration data are not included in tables because Weibull analysis was not considered to be appropriate.

Baseline SnPb data and other solder alloy/component finish data which is within 5% of the baseline is denoted with a 0. Single symbols, – or +, denote data that is 5% to 20% above (+) or below (-) the baseline. Double symbols, -- or ++, denote data that is more than 20% above (++) or below (--) the baseline. Green cells denote performance better than the SnPb baseline. Yellow cells denote performance worse than the SnPb baseline. Red cells denote data that is grossly worse than the SnPb baseline. Numerical values can be found in the "Weibull Numbers" Tables. Testing still in-progress is denoted with a P. Data that is not available or where there were not enough failures to rank the solders is denoted with a NA. Some test vehicles did not undergo certain tests which is denoted by an NT (not tested).

4.1 Vibration Test

4.1.1 Vibration Test Method

This test determined solder joint reliability during exposure to vibration and was performed in accordance with MIL-STD-810F *(Test Method Standard for Environmental Engineering Considerations and Laboratory Tests)*, Method 514.5 (Vibration).

The vibration test was run using the vibration power spectral density (PSD) inputs shown in Figure 4 and Table 6. Project technical representatives agreed that a stepwise vibration spectrum covering a wide array of intensities would best meet their requirements. The beginning 9.9 g_{rms} vibration level was selected because it represented an extreme real-life condition for the military airborne environment.

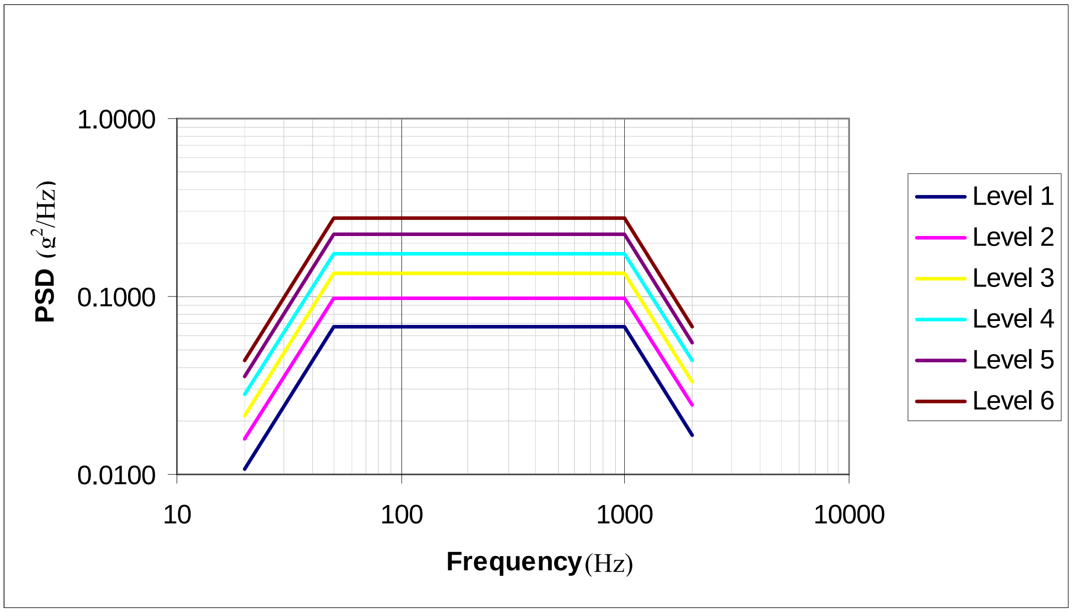

Figure 4 Vibration Spectrum

Table 7 Vibration Profile

Level 1			**Level 2**			**Level 3**		
20 Hz	@	0.0107 g²/Hz	20 Hz	@	0.0157 g²/Hz	20 Hz	@	0.0214 g²/Hz
20 - 50 Hz	@	+6.0 dB/oct	20 - 50 Hz	@	+6.0 dB/oct	20 - 50 Hz	@	+6.0 dB/oct
50 - 1000 Hz	@	0.067 g²/Hz	50 - 1000 Hz	@	0.0984 g²/Hz	50 - 1000 Hz	@	0.134 g²/Hz
1000 - 2000 Hz	@	-6.0 dB/oct	1000 - 2000 Hz	@	-6.0 dB/oct	1000 - 2000 Hz	@	-6.0 dB/oct
2000 Hz	@	0.0167 g²/Hz	2000 Hz	@	0.0245 g²/Hz	2000 Hz	@	0.0334 g²/Hz
Composite = 9.9 g_{rms}			Composite = 12.0 g_{rms}			Composite = 14.0 g_{rms}		
Level 4			**Level 5**			**Level 6**		
20 Hz	@	0.0279 g²/Hz	20 Hz	@	0.0354 g²/Hz	20 Hz	@	0.0437 g²/Hz
20 - 50 Hz	@	+6.0 dB/oct	20 - 50 Hz	@	+6.0 dB/oct	20 - 50 Hz	@	+6.0 dB/oct
50 - 1000 Hz	@	0.175 g²/Hz	50 - 1000 Hz	@	0.2215 g²/Hz	50 - 1000 Hz	@	0.2734 g²/Hz
1000 - 2000 Hz	@	-6.0 dB/oct	1000 - 2000 Hz	@	-6.0 dB/oct	1000 - 2000 Hz	@	-6.0 dB/oct
2000 Hz	@	0.0436 g²/Hz	2000 Hz	@	0.0552 g²/Hz	2000 Hz	@	0.0682 g²/Hz
Composite = 16.0 g_{rms}			Composite = 18.0 g_{rms}			Composite = 20.0 g_{rms}		

Table 8 Vibration Test Methodology

Parameters	• 1 hour per axis • Start at 9.9 g_{rms} in all three axes, then step up in 2 g_{rms} increments in the Z axis
Number and Type of Specimens	5 Printed Wiring Assemblies (PWAs) per solder alloy
Trials per Specimen	1
Acceptance Criteria	Electrical reliability better than or equal to tin/lead controls

4.1.2 Results for Vibration Testing

On the “Manufactured” test vehicles, the Pb-free solders under test sometimes performed as well or better than the eutectic SnPb control. For example, SACB was as reliable as SnPb with the

CLCC-20s and SnCu was the most reliable solder with the PDIP-20s (with both NiPdAu and matte tin component finishes).

In contrast, SnPb solder outperformed the Pb-free solders with the PLCCs. Only PLCC U15 exhibited failures, however, demonstrating that PLCCs are comparatively resistant to high vibration environments.

With the BGA-225s, the combination of eutectic SnPb solder/SnPb balls always outperformed the combination of Pb-free solder with Sn4.0Ag0.5Cu balls.

In some cases, the performance of the solders was mixed. For example, the orientation of the TSOP-50s may have played a role in how well the solders performed and in their relative ranking.

None of the TQFP vibration data was useful for comparing solder performance since most of the TQFP failures appeared to be due to broken leads and not failed solder joints.

Contamination of the Pb-free solders with Pb gave mixed results. For example, SACB was still the best performer with the CLCC-20s even when contaminated with large amounts of lead (approximately 17% Pb). With the BGA-225s, the combination of eutectic SnPb solder/SnPb balls outperformed the combinations of Pb-free solder/SnPb balls and SnPb solder/SAC balls.

SnPb generally outperformed the Pb–free solders on those components that were reworked. For BGA-225s that were reworked, SnPb balls assembled using flux only always outperformed SAC balls assembled using flux only. In the latter case, the final SAC solder joints contained approximately 0.3% Pb contamination from the residual SnPb left on the pads after removal of the SnPb component. For the PDIP-20s that were reworked (NiPdAu finish), SnPb solder was also the best performer. This is in sharp contrast to the results from the "Manufactured" vehicles where the SnCu wave solder alloy was the best performer. These results may be partly due to the negative effect that small amounts of Pb have on the reliability of SnCu.

The reworked TQFP U3 was unusual in that 7 out of 15 components had electrical opens before the test began. At least two of the seven bad components failed during normal handling between the time the test vehicles were received at Boeing and the vibration test was started. In addition, many of the U3 components fell off of the test vehicles during vibration testing. TQFP U3 and the adjacent BGAs (U4 and U18) were removed at the same time during rework. It is believed that replacement of the BGA-225s prior to replacement of TQFP U3 affected the U3 pads resulting in a weak pad/solder interface. In contrast, the other TQFP that was reworked (U57) did not exhibit premature electrical failure during normal handling and did not come off of the vehicle during vibration testing.

Since the PSD inputs were increased in a stepwise manner, it was felt that Weibull analysis might be inappropriate for the vibration data. Therefore, no ranking of solder performance based upon Weibull numbers was attempted. The reader is referred to the actual vibration test report contained within the Joint Test Report for a complete discussion of the vibration test results.

Table 9 lists the component/Pb-free solder/finish combinations that met the JTP acceptance criteria of solder joint reliability better than or equal to the eutectic SnPb controls.

Table 9 Vibration Test Samples Meeting the JTP Acceptance Criteria

Test Vehicle	Solder Alloy	Component Finish	Component Type
"Manufactured"	SnAgCuBi	SnAgCuBi	CLCC-20
"Manufactured"	SnAgCuBi	SnPb	CLCC-20
"Manufactured"	SnCu(Ni)	NiPdAu	PDIP-20
"Manufactured"	SnAgCu	NiPdAu	PDIP-20
"Manufactured"	SnCu(Ni)	Sn	PDIP-20

4.2 Mechanical Shock Test

4.2.1 Mechanical Shock Test Method

The purpose of this test was to measure solder joint failures during high-intensity shocks. Project technical representatives agreed to the need for two test procedures representing different shock scenarios. The first procedure addressed the requirements that many military customers have. For this procedure, MIL-STD-810F, Method 516.5 (Functional Test for Flight Equipment, Functional Test for Ground Equipment, and Crash Hazard Test for Ground Equipment), Procedure I (Functional Shock) was followed. This test is designed to test materiel (including mechanical, electrical, hydraulic, and electronic) in its functional mode and to assess the physical integrity, continuity and functionality of the materiel to shock. The second test procedure was a modified MIL-STD-810F, Method 516.5, intended to produce more failures than the first test procedure. For both test procedures, all three shock profiles from Method 516.5 were conducted (Figure 5).

In addition to meeting the requirements of MIL-STD-810F, Method 516.5, an increased number of shock transients were performed. One hundred shock cycles were performed in each direction along each of the 3 orthogonal axes for the Crash Hazard Test for Ground Equipment.

The first three shock profiles in the second test procedure mirrored those in the first test procedure except they were applied in the Z-axis only to minimize test time and maximize the number of failures.

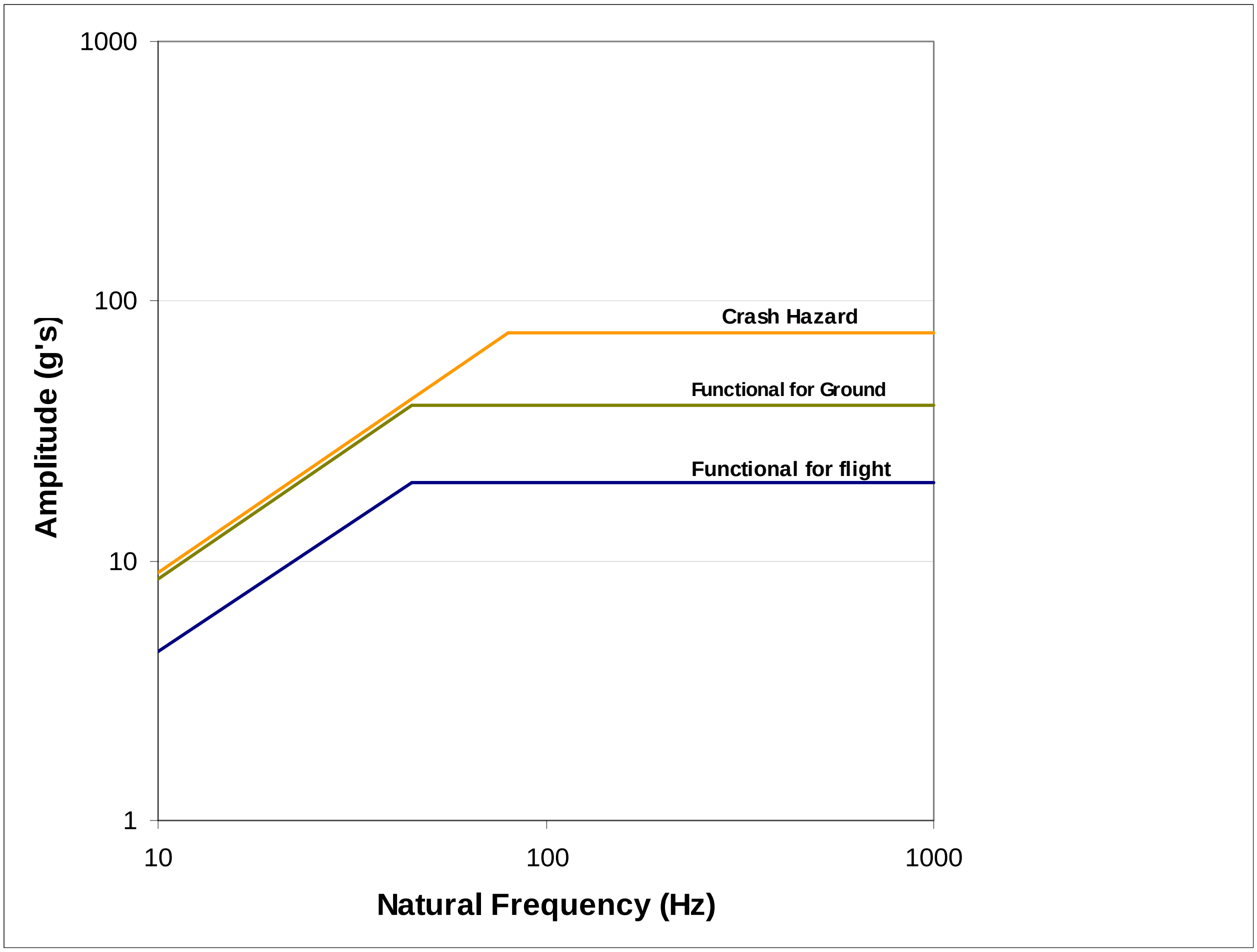

Figure 5 Mechanical Shock Response Spectrum – Test Procedure 1 and Test Procedure 2

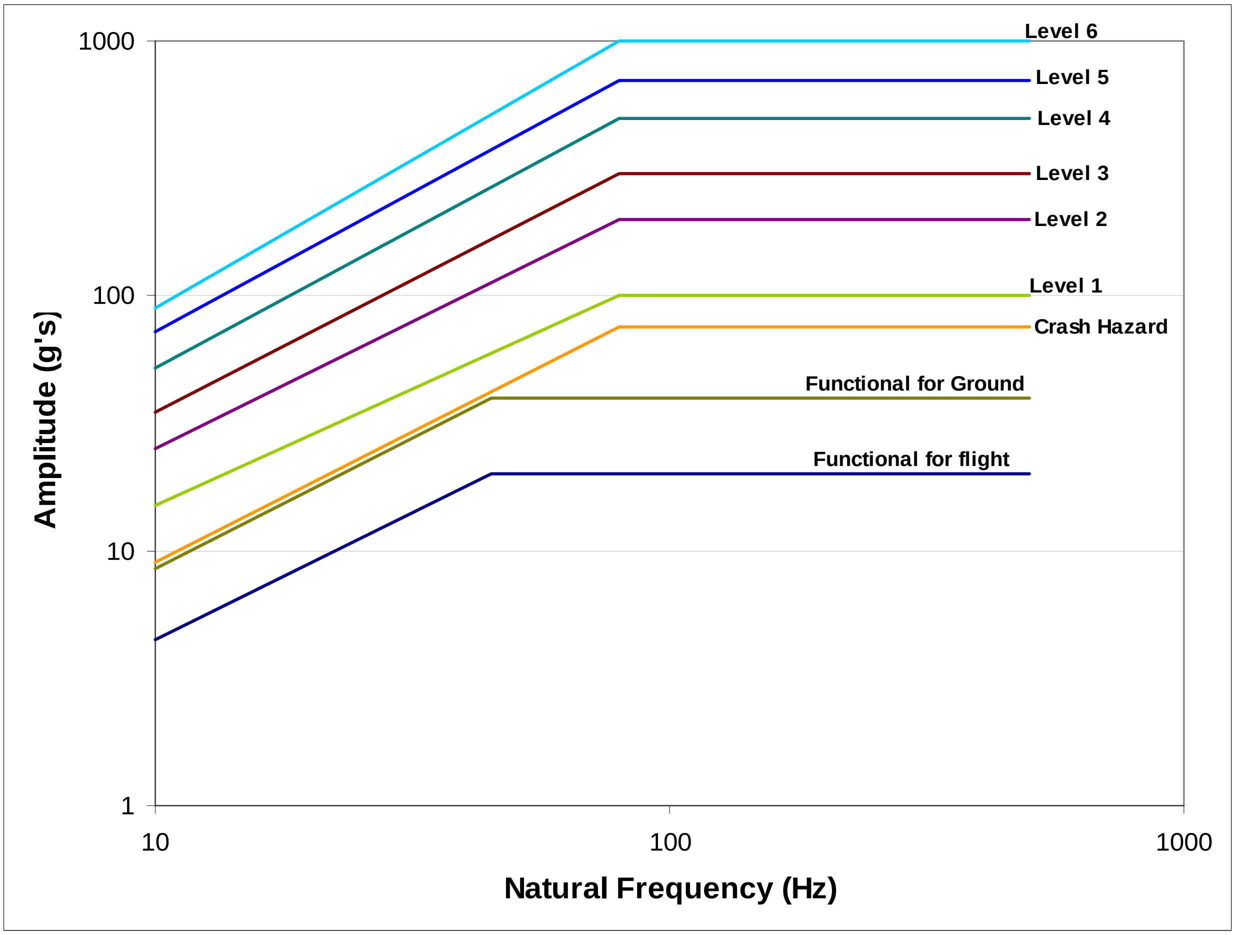

Figure 6 Mechanical Shock Response Spectrum – Additional Levels for Test Procedure 2

Table 10 Mechanical Shock Test Methodology – Test Procedure 1

<table>
<tr><td rowspan="5">Parameters</td><td colspan="9">• Apply three shock transients (Figure 5) in each direction along each of the 3 orthogonal axes for three test shock response spectra</td></tr>
<tr><td>Test Shock Response Spectra</td><td>Initial G</td><td>Slope</td><td>Peak G</td><td>Ts (ms)</td><td>Cross-Over Freq</td><td>Z-Axis</td><td>X-Axis</td><td>Y-Axis</td></tr>
<tr><td>Functional Test for Flight Equipment</td><td>4.5</td><td>6</td><td>20</td><td>15-23</td><td>45</td><td>3</td><td>3</td><td>3</td></tr>
<tr><td>Functional Test for Ground Equipment</td><td>8.5</td><td>6</td><td>40</td><td>15-23</td><td>45</td><td>3</td><td>3</td><td>3</td></tr>
<tr><td>Crash Hazard Test for Ground Equipment</td><td>9</td><td>6</td><td>75</td><td>8-13</td><td>80</td><td>3</td><td>3</td><td>3</td></tr>
<tr><td>Number and Type of Specimens</td><td colspan="9">• 2 PWAs per solder alloy for Test Procedure #1
• One “pathfinder” board</td></tr>
<tr><td>Acceptance Criteria</td><td colspan="9">• Electrical reliability better than or equal to tin/lead controls</td></tr>
</table>

Table 11 Mechanical Shock Test Methodology – Test Procedure 2

Parameters	• Apply the shock transients (Figure 6 in one axis parallel to the plane of the board, in a step-wise function, until a majority (≥ 63%) of all parts fail						
	Test Shock Response Spectra	Initial G	Slope	Peak G	Ts (ms)	Cross-Over Freq	Z-Axis
	Functional Test for Flight Equipment = Level 2.1	4.5	6	20	15-23	45	100
	Functional Test for Ground Equipment = Level 2.2	8.5	6	40	15-23	45	100
	Crash Hazard Test for Ground Equipment Level 2.3	9	6	75	8-13	80	100
	Level 2.4	12	6	100	15-23	80(1)	100
	Level 2.5	25	6	200	15-23	80(1)	100
	Level 2.6	35	6	300	15-23	80(1)	100
	Level 2.7	52	6	500	15-23	80(1)	100
	Level 2.8	72	6	700	15-23	80(1)	100
	Level 2.9	90	6	1000	15-23	80(1)	100(2)
Number and Type of Specimens	• 2 PWAs per solder alloy for Test Procedure #2 • One "pathfinder" board						
Acceptance Criteria	• Electrical reliability better than or equal to tin/lead controls						

4.2.2 Results for Mechanical Shock Testing

All alloys passed the mechanical shock test procedure 1, conducted per the environmental stress screening testing described in MIL-STD 810F; Method 516.5; Procedure 1. The SnPb and SAC soldered assemblies did not have any failures. The SACB soldered assemblies had three (3) TQFP-208 components and one (1) TSOP-50 component which failed.

For mechanical shock test procedure 2, at mechanical shock Test Level 2.1 (20 G Peak) through Test Level 2.3 (75 G Peak) there were very few failures during the tests so no definitive conclusions could be reached. Levels tested were consistent with the Functional Test for Flight Equipment levels, the Functional Test for Ground Equipment levels, and the Crash Hazard Test for Flight Equipment levels. 100 shocks were performed at each level in the Z-axis only. This was a more severe test than mechanical shock test procedure 1, where only three (3) shocks were provided in each axis.

At the higher mechanical shock test procedure 2 test levels, from test level 2.4 (100 G Peak) through Test Level 2.7 (500 G Peak), the test set-up recorded simultaneous failures of multiple devices with intermittent contact. A detailed review of the raw test data indicated that some failures were not related to the solder joints. Post test analysis revealed the failures were not at the solder joint level. It was concluded that SnPb and Pb –free solder joints survived the Functional Test for Flight Equipment, Functional Test for Ground Equipment, and Crash Hazard Test for Ground Equipment test levels. The test data at the high shock levels was inconclusive. Failures at the higher test levels could be attributed to:

- Electrical Interference: In conducting a review with BAE Systems, there were no detected power line disturbances or radiated EMI at that time of the test. BAE Systems have not experienced these types of failures since then. Therefore, this potential root cause of failure was eliminated.

- Wiring Failures: At the higher test levels, wiring failures would account for open circuits detected, but not for intermittent failures. Therefore, this potential root cause of failure was eliminated.

- Internal Component Damage: This would have resulted in a complete open failure of the daisy chain circuit. X-Ray analysis on specific failed components did not yield a complete answer.

- Board Damage: This would have resulted in a complete open or an intermittent failure within the daisy chain circuit.

- Connector Failures: In reviewing the connector's product data sheet, the connectors were rated for 50G peak per MIL-STD-202, Method 213; Condition G. This is below the 100G level at Test Level 2.4. It is speculated that an instantaneous open in the connector contact at the barrel was considered to be a major cause of failure.

Based upon the failure analysis investigations to identify the root cause of solder joint failures, it was concluded that the open circuits detected were attributed to connector failures or failures at the board traces.

ACI performed a limited Failure Mode Analysis (FMA) on BGA-225 components. Solder joint cross sections found several BGA solder balls had partially traversed cracks, but no complete failure.

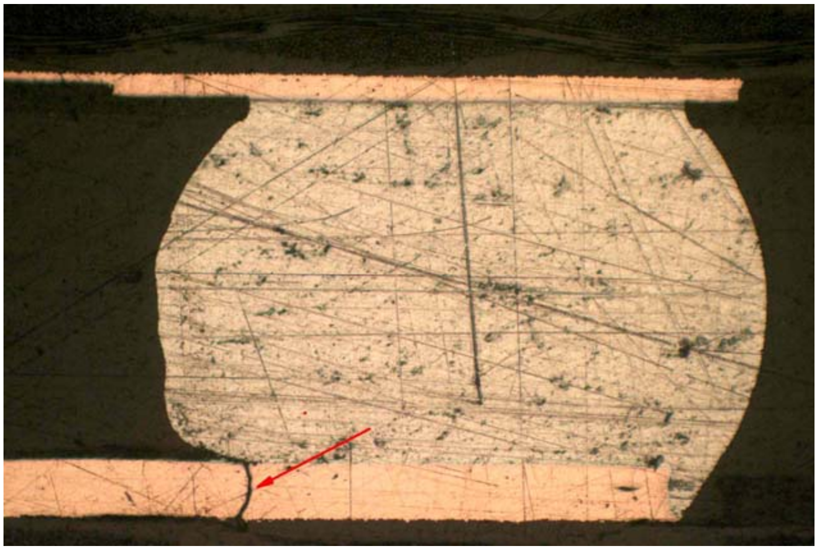

Figure 7 Broad 29, SnPb "Manufactured", BGA U44, PCB trace failure at BGA Ball 1R, illustrating a complete failure

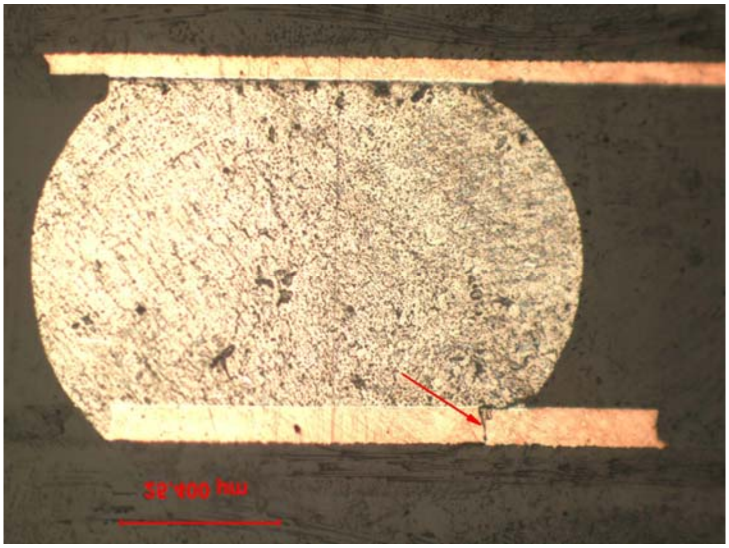

Figure 8 Board 97, SAC/SAC, BGA U44, PCB trace failure at BGA Ball 1B; As can be seen this failure could cause intermittent electrical failures

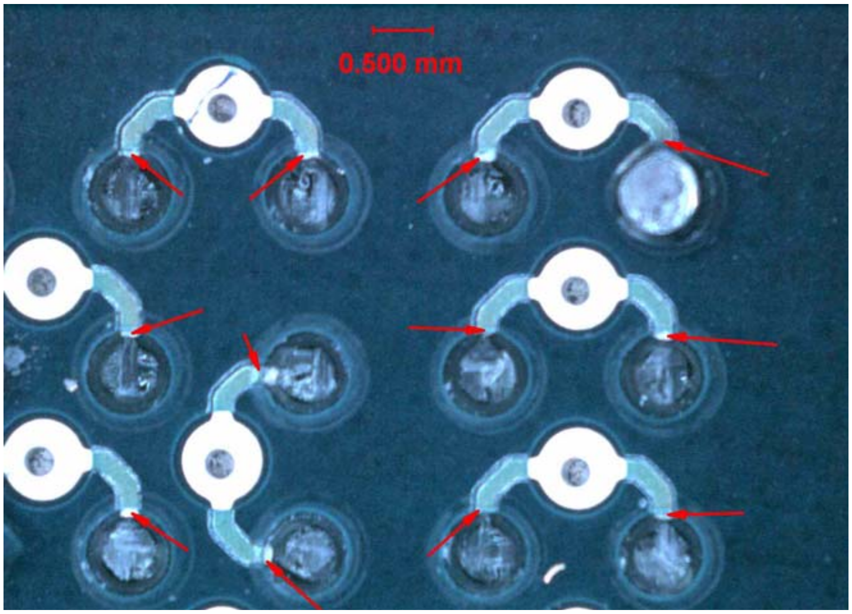

Figure 9 Example of PCB Trace failures in the corner of the BGA. Land Pads lifted cleanly, separating at the conductor to land pad interfaces indicating a cracked conductors. The area of separation was oxidized.

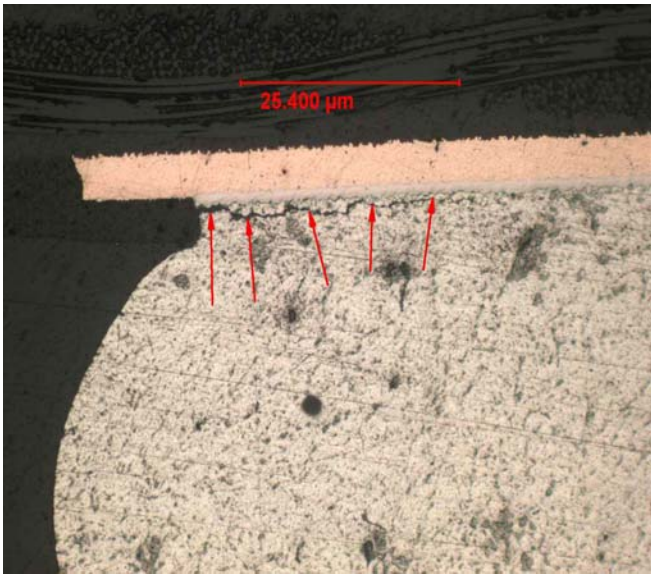

Figure 10 Example of Solder Ball cracked on the component side. No failures of this type found but small amount of cracking seen.

Intermittent test failures were a serious cause of concern. However, it was felt that these intermittent failures were caused by the spring tension on the solder joint leads and making and breaking of contacts in each pulse. As a result, we felt that the failures were coming from the solder joints instead of extraneous sources. Therefore, the test was continued until the test level 2.7.

A series of Lessons Learned were developed for future mechanical shock tests at High G levels:

- All data collection wires should be soldered directly into the test vehicle. Connectors should not be used unless rated above the shock test levels.
- All wires and cables connected to the test vehicle should be shielded to prevent any potential effects from Electromagnetic Interference.
- Hardware and data recording equipment should be grounded to earth ground, or a clean electrical system ground.
- A thorough failure mode analysis (FMA) of all failed assemblies is recommended to verify the solder performance at Hi-G levels of mechanical shock.

4.3 Combined Environments Test

4.3.1 Combined Environments Test Method

The Combined Environments Test (CET) was based on a modified Highly Accelerated Life Test (HALT), a process in which products are subjected to accelerated environments to find weak links in the design and/or manufacturing process.

This test was conducted in accordance with the following procedure. The test was performed utilizing a temperature range of –55°C to +125°C with 20°C/minute ramps. The dwell times at each temperature extreme were the times required to stabilize the test sample plus a 15-minute soak. 10 g_{rms} pseudo-random vibration was applied for the last 10 minutes of the cold and hot soaks. Testing was continued until sufficient data was generated to obtain statistically significant Weibull plots indicating relative solder joint endurance (cycles to failure) rates. If significant failure rates were not evidenced after 50 cycles, the vibration levels were incremented by 5 g_{rms} and cycling continued for an additional 50 cycles. This process was repeated until all parts failed or 55 g_{rms} was reached. During cycles 501 through 550, the vibration was continuous throughout the cycle.

Table 12 Combined Environments Test Methodology

Parameters	• -55°C to +125°C • Number of cycles ≥ 500 • 20°C/minute ramp • 15 minute soak • Vibration last 10 minutes of soak period • 10 Grms, initial • Increase 5 Grms after every 50 cycles • 55 Grms, maximum
Number and Type of Specimens	5 PWAs per solder alloy
Trials per Specimens	1
Acceptance Criteria	Electrical reliability better than or equal to tin/lead controls

4.3.2 Results for Combined Environments Test

The “Manufactured” test vehicles were tested for 550 cycles. Test vehicles soldered with SACB solder had the fewest number of solder joints fail (59 % of the components registering as a failure). Test vehicles soldered with SnPb solder were second best (63 % of the components registering as a failure). The test vehicles soldered with SAC had the worst performance (73 % of the components registering as a failure). The plated through-holes, PLCC-20 and PDIP-20 experienced little or no failures. No additional data analysis was conducted on these components. Not enough plated through-hole components failed to be able to rate the performance of the wave solder alloys. The remaining failure data were analyzed with ReliaSoft Weibull++6 software using 2-parameter Weibull analysis.

The “Rework” test vehicles were tested for 550 cycles. The HALT chamber experienced an over temperature condition during cycle 537. The failure data were truncated at 536 cycles. Test vehicles reworked with SnPb solder had the best performance with 74 % of the reworked components registering as a failure. Test vehicles reworked with SAC had the next best performance with 86 % of the reworked components registering as a failure. Test vehicles reworked with SACB solder had the most solder joints fail at 100 % of the reworked components registering as a failure. In general, reworked components failed more often than the un-reworked components. The exception to this trend was the reworked BGA-225 components. Use of the hot air rework station may have exposed the BGA-225 components to hotter temperatures than they experienced during the original reflow solder process. The higher temperatures may have provided better solder melting and improved the solder joint reliability.

The "Hybrid" test vehicles were tested for 500 cycles. Test vehicles soldered with SACB solder had fewer solder joints fail with 82 % of the components registering as a failure. The test vehicles soldered with SAC had the next best performance with 92 % of the components registering as a failure. Test vehicles soldered with SnPb solder were worst with 100 % of the components registering as a failure.

The combined environments test results are summarized in Figure 11. The graph summarizes the N(10%) values for the different component types, component finishes and solder alloys compared to the SnPb controls. The shaded area of the graph shows the 95% confidence intervals for the SnPb controls. Data within the bounded area indicate the Pb-free soldered components that have similar performance to the SnPb controls. Data outside the bounded area indicate the Pb-free soldered components have significantly different (better or worse) performance compared to the SnPb controls. In general, SAC soldered components had a higher failure rate than the SnPb soldered controls. The components are listed along the x-axis in order from lower to higher reliability.

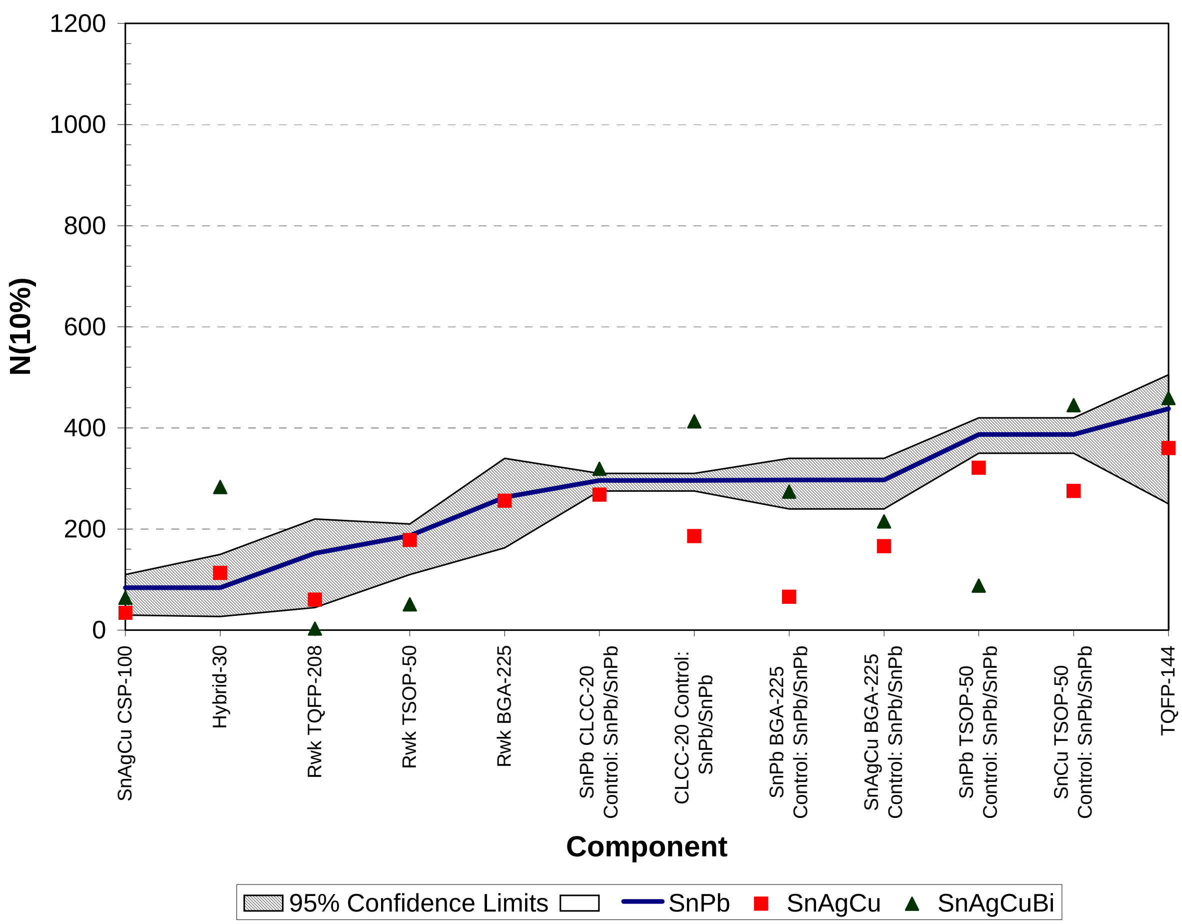

Figure 11 Pb-free Solders Compared to Tin Lead Controls Based on N(10%)

Only seven Pb-free soldered samples met the JTP acceptance criteria of Pb-free solder joint reliability better than or equal to eutectic SnPb controls at ten percent Weibull cumulative failures. The seven samples are tabulated below. Those samples include SACB soldered CLCC-20 components, TQFP-144 components and SnCu TSOP-50 components on "Manufactured" test vehicles, and SACB hybrid-30 components on "Hybrid" test vehicles. The only SAC soldered components that met the JTP acceptance criteria were the reworked BGA-225 on rework test vehicles and SAC hybrid-30 on "Hybrid" test vehicles. There were not enough failures of the more robust plated through-hole parts to compare the performance of the SAC and SnCu solder alloys used in wave solder.

Table 13 Solder Performance During Combined Environments Testing

Solder Performance				
Component	**Solder/Finish**	**1st Failure**	**N10**	**N63**
BGA-225	SnPb/SnPb	175	297	504
	SAC/SAC	100	166	317
	SACB/SAC	1 (137)	215	394
	SAC/SnPb	30	66	385
	SACB/SnPb	223	274	445
CLCC-20	SnPb/SnPb	259	296	369
	SAC/SAC	168	186	260
	SACB/SACB	1 (363)	413	507
	SAC/SnPb	230	268	326
	SACB/SnPb	302	319	410
TQFP-144	SnPb/Sn	327	438	667
	SAC/Sn	308	360	566
	SACB/Sn	29 (353)	459	653
TSOP-50	SnPb/SnPb	347	387	516
	SAC/SnCu	221	275	392
	SACB/SnCu	367	445	595
	SAC/SnPb	301	321	428
	SACB/SnPb	51	88	220
CSP-100	SnPb/SnPb	15	84	287
	SAC/SAC	24	34	171
	SACB/SAC	2 (36)	64	145
Hybrid-30	SnPb/SnPb	36	84	319
	SAC/SAC	105	113	310
	SACB/SACB	232	283	500
Rwk BGA-225	NA/SnPb	252	263	336
	NA/SAC	169	256	458
Rwk TQFP-208	SnPb/NiPdAu	148	152	365
	SAC/NiPdAu	52	60	385
	SACB/NiPdAu	2	3	169
Rwk TSOP-50	SnPb/SnPb	186	187	281
	SAC/SnCu	156	178	375
	SACB/SnCu	22	51	226

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Table 14 Relative Solder Performance During Combined Environments Testing

Relative Solder Performance				
Component	**Solder/Finish**	**1st Failure**	**N10**	**N63**
BGA-225	SnPb/SnPb	0	0	0
	SAC/SAC	--	--	--
	SACB/SAC	--	--	--
	SAC/SnPb	--	--	--
	SACB/SnPb	++	-	-
CLCC-20	SnPb/SnPb	0	0	0
	SAC/SAC	--	--	--
	SACB/SACB	++	++	++
	SAC/SnPb	-	-	-
	SACB/SnPb	+	+	+
TQFP-144	SnPb/Sn	0	0	0
	SAC/Sn	-	-	-
	SACB/Sn	+	0	0
TSOP-50	SnPb/SnPb	0	0	0
	SAC/SnCu	--	--	--
	SACB/SnCu	+	+	+
	SAC/SnPb	-	-	-
	SACB/SnPb	--	--	--
CSP-100	SnPb/SnPb	0	0	0
	SAC/SAC	++	--	--
	SACB/SAC	++	--	--
Hybrid-30	SnPb/SnPb	0	0	0
	SAC/SAC	++	++	0
	SACB/SACB	++	++	++
Rwk BGA-225	NA/SnPb	0	0	0
	NA/SAC	--	0	++
Rwk TQFP-208	SnPb/NiPdAu	0	0	0
	SAC/NiPdAu	--	--	+
	SACB/NiPdAu	--	--	--
Rwk TSOP-50	SnPb/SnPb	0	0	0
	SAC/SnCu	-	0	++
	SACB/SnCu	--	--	-

Table 15 Combined Environment Test Samples Meeting the JTP Acceptance Criteria

Test Vehicle	Solder Alloy	Component Finish	Component Type
"Manufactured"	SACB	SACB	CLCC-20
"Manufactured"	SACB	SnPb	CLCC-20
"Manufactured"	SACB	Sn	TQFP-144
"Manufactured"	SACB	SnCu	TSOP-50
"Rework"	N/A	SAC	BGA-225
"Hybrid"	SACB	SACB	Hybrid-30
"Hybrid"	SAC	SAC	Hybrid-30

4.4 Thermal Shock Test

4.4.1 Thermal Shock Test Method

This test determined solder joint reliability under thermal shock conditions. This test was performed in accordance with MIL-STD-810F, Method 503.4, Procedure I (Temperature Shock Steady State).

Table 16 Thermal Shock Test Methodology

Parameters	• -55°C to +125°C • 1000 shock cycles • 10 sec, max transfer • 15 minute dwells
Number and Type of Specimens	5 PWAs per solder alloy
Trials per Specimen	1
Acceptance Criteria	Electrical reliability better than or equal to tin/lead controls

4.4.2 Results for Thermal Shock Testing

Most of the components exposed to 1000 cycles of -55°C to +125°C thermal shock did not fail. The CLCC-20s did have a large percentage of failures, however. Based solely on the data from the CLCC-20 failures, SnPb is more reliable than SACB which in turn is more reliable than SAC.

Contamination of the Pb-free CLCC-20 solder joints with large amounts of lead (17%) only resulted in a modest decrease in the reliability of the Pb-free solders (SAC and SACB). Pb-contamination was expected to have a large negative effect on the reliability of SACB due to the formation of the low melting ternary 16Sn32Pb52Bi alloy. It is not understood why it did not.

In contrast, contamination of Pb-free TSOP-50 solder joints with small amounts of lead (3%) resulted in a large decrease in the reliability of SACB. This negative effect of small amounts of lead on the reliability of bismuth-containing solders has been previously observed. To ensure maximum reliability, SACB solder should not be used when there is a chance that it may be mixed with SnPb solder.

SnPb solder used in combination with SAC or SACB component finishes grossly underperformed the combination of SnPb solder with a SnPb finish. Since a SnPb reflow profile was used, mixing of the SnPb solder and the Pb-free finishes was expected to be minimal, but Inductively Coupled Plasma (ICP) analysis suggested that solder mixing did occur. To ensure maximum reliability, SnPb solders should not be used with SAC or SACB component finishes (e.g., SAC BGA balls).

SnPb balls assembled with SAC paste failed on six out of a total of 25 BGA-225s. This suggests that using SnPb BGA-225s in combination with SAC solder is to be avoided. In comparison, only one failure was seen when SACB paste was used with SnPb balls.

No BGA-225 failures were observed for the combinations of SnPb paste/SnPb balls; SAC paste/SAC balls; or SACB paste/SAC balls.

Rework did have a negative effect on some components. During rework with the Pb-free solders, the old component was removed; the pads were wicked clean of most but not all of the SnPb; and a new component was attached using a Pb-free solder. Therefore, all solder joints on the "Rework" test vehicles contained lead, even the components that were reworked. The effects of lead contamination and the effects (if any) of the heat of the rework operation upon the reliability of the solder joints in this test are not readily separable from each other.

TSOP-50s reworked with SACB had a greatly reduced reliability compared to the SnPb control (not reworked). This could be due to the formation of the 16Sn32Pb52Bi alloy. Surprisingly, the TSOP-50s reworked with SnPb also show reduced reliability compared to the SnPb control (not reworked). Since Pb contamination can not be blamed, this effect must be due to the heat of the rework operation alone. The TSOP-50s reworked with SAC were as reliable as the SnPb control (not reworked).

TQFP U3 exhibited numerous failures when reworked with SAC or SACB but not with SnPb. The supposedly identical TQFP U57 did not exhibit any failures. TQFP U3 and the adjacent BGAs (U4 and U18) were removed at the same time during rework. It is believed that replacement of the BGA-225s prior to replacement of TQFP U3 affected the U3 pads resulting in a weak pad/solder interface.

In general, it appears that rework operations have the potential to reduce the reliability of both Pb-free and SnPb solders. The results of the thermal cycling tests may better reveal trends due to rework since more failures were generated.

The thermal shock test results are summarized in Figure 12 and Table 17 and Table 18. Figure 12 shows the Weibull N(10%) values for the different component/solder/finish combinations compared to the SnPb controls. The shaded area of the graph shows the 95% confidence intervals for the SnPb controls. Data within the bounded area indicate that the Pb-free soldered components have similar performance to the SnPb controls. Data outside the bounded area indicate the Pb-free soldered components have significantly different (better or worse) performance compared to the SnPb controls. Table 16 and Table 17 show the solder joint first failure numbers and the Weibull N(10%) and N(63%) numbers.

Table 19 and Table 20 show the relative ranking of the solders for each component type based on the first failure, Weibull N(10%), and Weibull N(63%) numbers.

For those components that had solder joint failures, most of the Pb-free solders tested did not meet the JTP acceptance criteria of solder joint reliability better than or equal to the eutectic SnPb controls (when comparing the ten percent Weibull cumulative failure numbers). The exceptions were TSOP-50 components reworked with SAC.

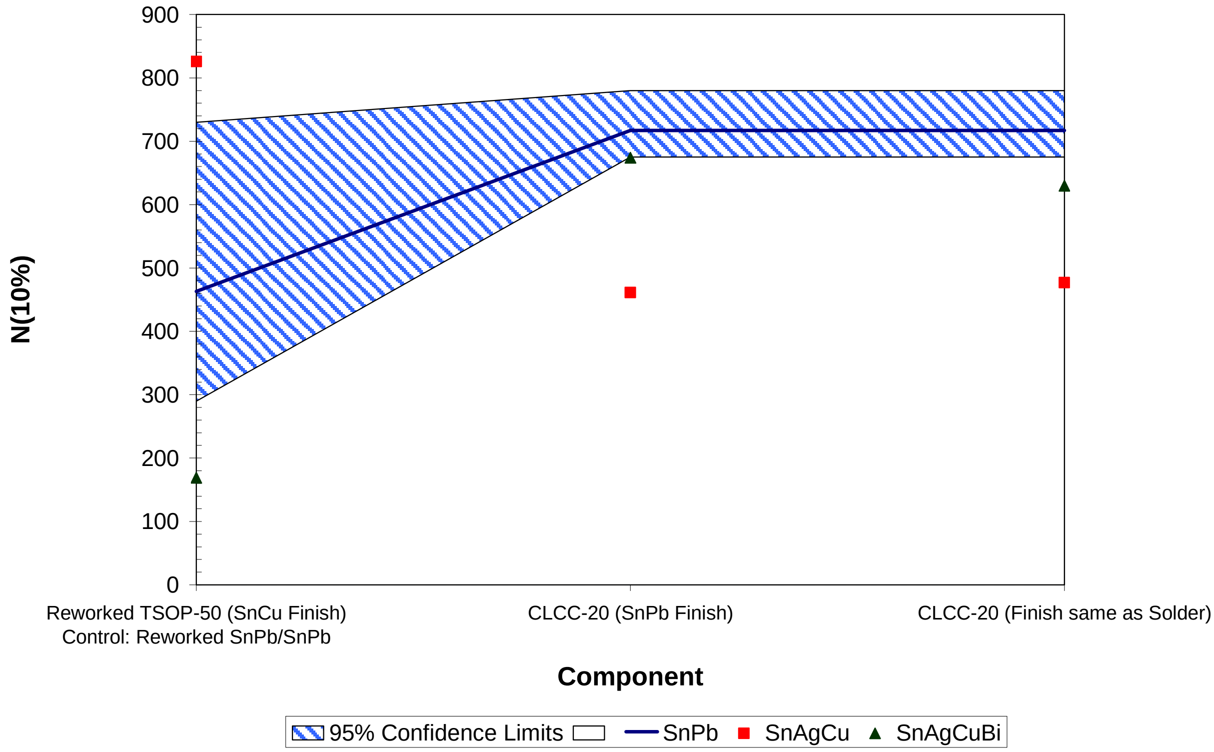

Figure 12 Pb-free Solders Compared to Tin Lead Controls based on Weibull N(10%), "Manufactured" and "Rework" Thermal Shock Test Vehicles

Table 17 Weibull Numbers from the Thermal Shock Test, "Manufactured" Test Vehicles

Solder Performance -55 to 125°C Thermal Shock "Manufactured" Test Vehicles				
Component	**Solder/Finish**	**1st Failure**	**N10**	**N63**
CLCC-20	SnPb/SnPb	627	717	931
	SAC/SAC	79 (392)	477	681
	SACB/SACB	525	630	869
	SAC/SnPb	404	461	635
	SACB/SnPb	657	674	789
TSOP-50	SnPb/SnPb	961	NA	>1000
	SAC/SnCu	144, 278 (880)	NA	>1000
	SACB/SnCu	>1000	>1000	>1000
	SAC/SnPb	229, 250 (821)	NA	>1000
	SACB/SnPb	174	235	489
BGA-225	SnPb/SnPb	>1000	>1000	>1000
	SAC/SAC	>1000	>1000	>1000
	SACB/SAC	>1000	>1000	>1000
	SAC/SnPb	162	315	>1000
	SACB/SnPb	195	>1000	>1000

NA = Not enough failures to accurately determine

Table 18 Weibull Numbers from the Thermal Shock Test, "Rework" Test Vehicles

Solder Performance -55 to 125°C Thermal Shock "Rework" Test Vehicles				
Component	**Solder/Finish**	**1st Failure**	**N10**	**N63**
BGA-225	SnPb/SnPb	>1000	>1000	>1000
	SnPb/SAC	135	388	NA
CLCC-20	SnPb/SnPb	533	680	961
	SnPb/SAC	315	373	568
	SnPb/SACB	300	350	528
TSOP-50	SnPb/SnPb	596	829	1099
	SnPb/SnCu	565	778	1069
Reworked TSOP-50	SnPb/SnPb (After Rework)	415	463	978
	SAC/SnCu (After Rework)	783	826	1110
	SACB/SnCu (After Rework)	157	169	406
Reworked TQFP-208 (U3 Only)	SnPb/NiPdAu (After Rework)	>1000	>1000	>1000
	SAC/NiPdAu (After Rework)	182	200	675
	SACB/NiPdAu (After Rework)	17	19	150

NA = Not enough failures to accurately determine

Table 19 Relative Solder Performance During Thermal Shock Testing, "Manufactured" Test Vehicles

Relative Solder Performance -55 to +125°C Thermal Shock "Manufactured" Test Vehicles				
Component	**Solder/Finish**	**1st Failure**	**N10**	**N63**
CLCC-20	SnPb/SnPb	0	0	0
	SAC/SAC	--	--	--
	SACB/SACB	-	-	-
	SAC/SnPb	--	--	--
	SACB/SnPb	0	-	-
TSOP-50	SnPb/SnPb	0	0	0
	SAC/SnCu	-	NA	NA
	SACB/SnCu		NA	NA
	SAC/SnPb	-	NA	NA
	SACB/SnPb	--	--	--
BGA-225	SnPb/SnPb	0	0	0
	SAC/SAC	NA	NA	NA
	SACB/SAC	NA	NA	NA
	SAC/SnPb	--	--	NA
	SACB/SnPb	--	NA	NA

NA = Not enough failures to rank
0= Same as Control (5% or less difference)

Table 20 Relative Solder Performance During Thermal Shock Testing, "Rework" Test Vehicles

Relative Solder Performance -55 to +125°C Thermal Shock "Rework" Test Vehicles				
Component	**Solder/Finish**	**1st Failure**	**N10**	**N63**
BGA-225	SnPb/SnPb	0	0	0
	SnPb/SAC	--	--	NA
CLCC-20	SnPb/SnPb	0	0	0
	SnPb/SAC	--	--	--
	SnPb/SACB	--	--	--
TSOP-50	SnPb/SnPb	0	0	0
	SnPb/SnCu	-	-	0
Reworked TSOP-50	SnPb/SnPb (After Rework)	0	0	0
	SAC/SnCu (After Rework)	++	++	+
	SACB/SnCu (After Rework)	--	--	--
Reworked BGA-225	Flux/SnPb (After Rework)	NA	NA	NA
	Flux/SAC (After Rework)	NA	NA	NA
Reworked TQFP-208 (U3 Only)	SnPb/NiPdAu (After Rework)	0	0	0
	SAC/NiPdAu (After Rework)	--	--	--
	SACB/NiPdAu (After Rework)	--	--	--

NA = Not enough failures to rank
0= Same as Control (5% or less difference)

4.5 Thermal Cycle -55°C to +125°C Test

4.5.1 Thermal Cycle -55°C to +125°C Test Method

The -55°C to +125°C thermal cycle testing was conducted in accordance with IPC-SM-785 *"Guidelines for Accelerated Reliability Testing of Surface Mount Solder Attachments"*. This temperature range was one of two selected by the project technical representatives because it is a representative thermal cycle temperature range for both aerospace and defense products. The project technical representatives after examining the available data on dwell time effect agreed to use a high-temperature dwell time of 30 minutes instead of the standard 10 minutes. Solder alloy creep during the high temperature dwell segment of the thermal cycle is largely responsible for damage within the solder joints.

Table 21 Thermal Cycling Test Methodology; -55°C to +125°C

Parameters, "Manufactured" Test Vehicles	• -55°C to +125°C • Cycles: Until 63% failures or greater • Decision point at 5000 cycles if 63% failure not yet achieved • 5 to 10°C/minute ramp • 30 minute high temperature dwell • 10 minute low temperature dwell
Parameters, "Rework" Test Vehicles	• -55°C to +125°C • Cycles: Until 63% failures or greater • Decision point at 5000 cycles if 63% failure not yet achieved • 5 to10°C/minute ramp • 30 minute high temperature dwell • 10 minute low temperature dwell
Number and Type of Specimens	5 PWAs per solder alloy
Trials per Specimen	1
Acceptance Criteria	Electrical reliability better than or equal to tin/lead controls

4.5.2 **Results for Thermal Cycle -55°C to +125°C Testing**

A complete statistical analysis and extensive failure analysis was completed for the -55°C to +125°C thermal cycle test after the completion of 4743 total cycles. A summary of the statistical analysis is listed below:

BGA-225 results:
By the end of testing, 85.7% (257 of 300) of the BGA-225 component total population had failed. On the "Manufactured" test vehicles (170°C Tg), both the SACB and SAC solder alloys had better performance that the SnPb solder alloy. The Weibull plots show two early BGA-225 SAC/SAC, i.e. SAC solder/SAC solderpaste, failures that resulted in a significantly lower Weibull slope for this combination compared to the others. Due to these two early failures, the SAC/SAC combination had a much lower first failure than the other combinations. Also, the Pb-free solders with SnPb solderballs exhibited lower (SAC/SnPb) or essentially the same (SACB/SnPb) reliability as SnPb/SnPb components. However, the average and characteristic lives of the Pb-free (SAC or SACB solder with SAC surface finish) BGA-225s were 30% to 50% higher than of the Sn/Pb components. On the "Rework" test vehicles (140°C Tg), the reworked SnPb solderpaste/SAC solderball mixed metallurgy combination had a much lower Weibull slope than the other solderpaste/solderball combinations. In other words, the failures were distributed over a much wider range of thermal cycles, indicating a that the reworked SAC solder joints were not as consistent as those made with other material combinations.

CLCC-20 results:
The CLCC-20 components were one of only two component types that experienced 100% population failure during this testing. The CLCC-20 components were included on the test vehicles because of their poor reliability track record on electronic assemblies used in harsh environments. CLCC-20 components with three different alloy/finish combinations (SAC/SAC, SACB/SACB, SnPb/SnPb) were tested and the results showed statistically significant differences in thermal cycle reliability. On the "Manufactured" test vehicles (170°C Tg), the characteristic life of the SAC solder alloy was approximately 200 cycles less than the SACB or SnPb solder alloys. On the "Rework" test vehicles (140°C Tg), the components with SnPb solder had nearly twice the fatigue life of either the SAC and SACB components. Note that the reliability of the CLCC-20 components with SnPb solder was essentially the same whether they were on the "Manufactured" or the "Rework" test vehicles.

TQFPs results:
The TQFP-144 components failed 90.7% (136 of 150) of the total test population after 4743 thermal cycles. These tests included all three solder pastes (SAC, SACB, and SnPb) with only one surface finish (Sn). On the "Manufactured" test vehicles (170°C Tg), the TQFP-144 components assembled with SACB solderpaste had ~40% better reliability than the SnPb components. The components assembled with SAC had a similar characteristic life (N63) to those with the other solderpaste, but a significantly lower Weibull slope. This result again suggests that the SAC solder joints were less consistent than those assembled with either SnPb or SACB. TQFP-144 components assembled with SnPb on "Rework" test vehicles had virtually the same slope (consistency) as parts on "Manufactured" boards, but lower characteristic life (1977 vs. 2672).

The TQFP-208 components failed 73.3% (110 of 150) of the total test population after 4743 thermal cycles. On the "Manufactured" test vehicles (170°C Tg), there was at least one early failure for all three solder alloys investigated. Except for two early failures, the SAC TQFP-208 components had similar reliability behavior as the SnPb components, i.e. the slopes and characteristic life are similar. Typically, a Weibull slope of less than 1.0, as in the case of the TQFP-208 components with SACB, is considered to indicate infant mortality failures. This clearly indicates that if consistent solder joints can be created with SACB, these parts would be significantly more reliable than with SnPb.

On the "Rework" test vehicles (140°C Tg), the reworked TQFP-208 components had significantly shorter life (> 700 thermal cycles) than the non-reworked TQFP-208 components. The statistical results document the poor performance of the reworked SACB solder alloy in comparison to SAC and SnPb. A review of the TQFP rework protocol reviewed the cause of poor reworked components performance. The TQFP component was the last of a group of four components reworked in a closely grouped test vehicle region. The TQFP component pads were repeatedly oxidized during the replacement soldering of the other three components thus impacting the TQFP rework final solder joint integrity.

TSOP-50 results:
The TSOP-50 components also experienced 100% population failure by the end of testing. The TSOP-50 components used in this testing had two different lead finishes (SnCu and SnPb) and were assembled with three solderpaste alloy combinations (SnPb, SAC, SACB). The TSOP-50 components assembled on "Manufactured" test vehicles with SnPb and SAC solderpaste had essentially the same reliability regardless of surface finish (SnCu or SnPb). However, when

SACB solderpaste was used, the surface finish had a significant effect. SACB solder with SnPb surface finish had significantly poorer reliability while SACB with SnCu finish had significantly better reliability than the other combinations (Figure 13). On the “Rework” test vehicles, the SAC/SnCu and SnPb/SnCu solderpaste/surface finish combinations had essentially the same reliability as SnPb/SnPb components while SACB/SnCu and reworked SnPb/SnPb components had somewhat lower reliability.

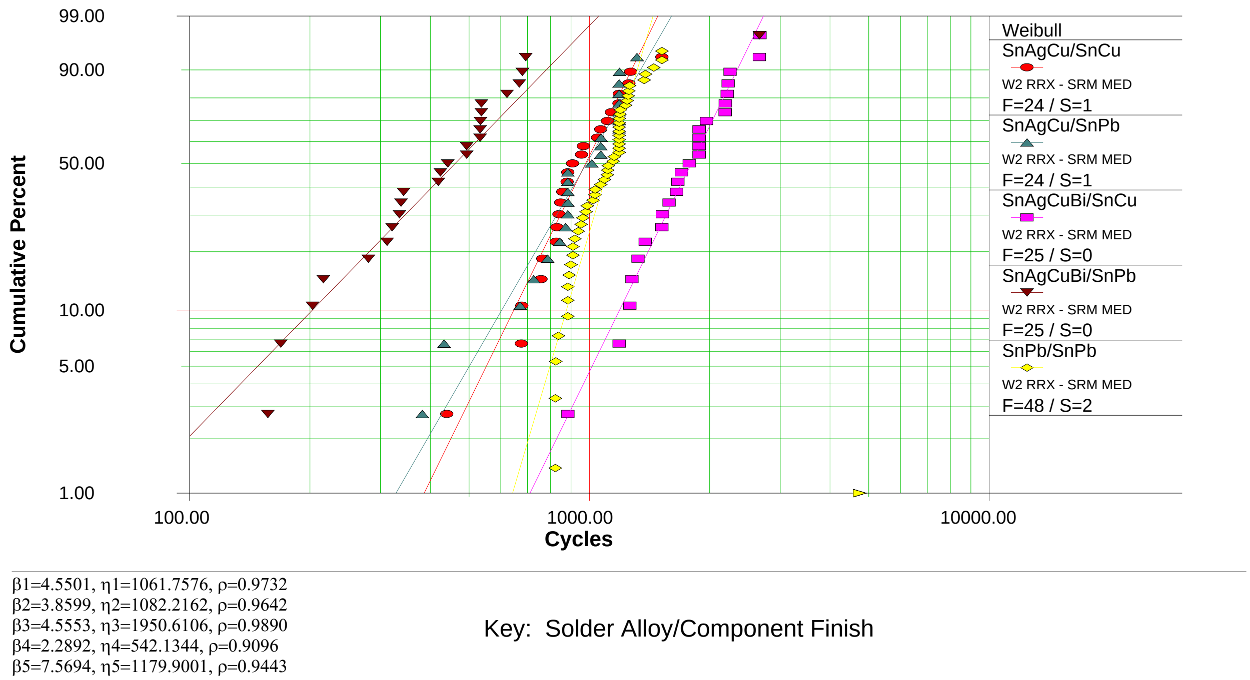

Figure 13 Weibull Plot of TSOP-50 Data

PDIP-20 results:
The PDIP-20 components failed 8% (24 of 300) of the total test population after 4743 thermal cycles. The low component failure totals made the creation of Weibull plots meaningless for either the “Manufactured” or “Rework” test vehicles. Each solderpaste/surface finish combination for the PDIP-20 components experienced at least one failure before 1500 thermal cycles but no more than 2 failures by the end of testing at 4743 cycles. This, along with the calculated Weibull slopes of ~1 or less, indicates that these failures were likely due to infant mortality. The low overall failure rate of the PDIP-20 components of 8% is indicative of the good reliability of that packaging style. However, the relatively consistent early failure trend (5 of the 6 combinations had a failure by 900 cycles) does demonstrate that there can be challenges in achieving 100% manufacturing consistency.

PLCC-20
The PLCC-20 components failed 5.3% (8 of 150) of the total test population after 4743 thermal cycles. The low component failure totals made the creation of Weibull plots meaningless for either the “Manufactured” or “Rework” test vehicles. The lack of failures reflects the overall good performance of the PLCC-20 component type.

The -55°C to +125°C thermal cycle test results are summarized in Figure 14. The graph summarizes the N(10%) values for the different component types, component finishes and solder alloys compared to the SnPb controls. The shaded area of the graph shows the 95% confidence intervals for the SnPb controls. Data within the bounded area indicate the Pb-free soldered components have similar performance to the SnPb controls. Data outside the bounded area indicate the Pb-free soldered components have significantly different (better or worse) performance compared to the SnPb controls. In general, CLCC-20, TSOP-50, and reworked components had a higher failure rate than the SnPb soldered controls. The components are listed along the x-axis in order from low to higher reliability.

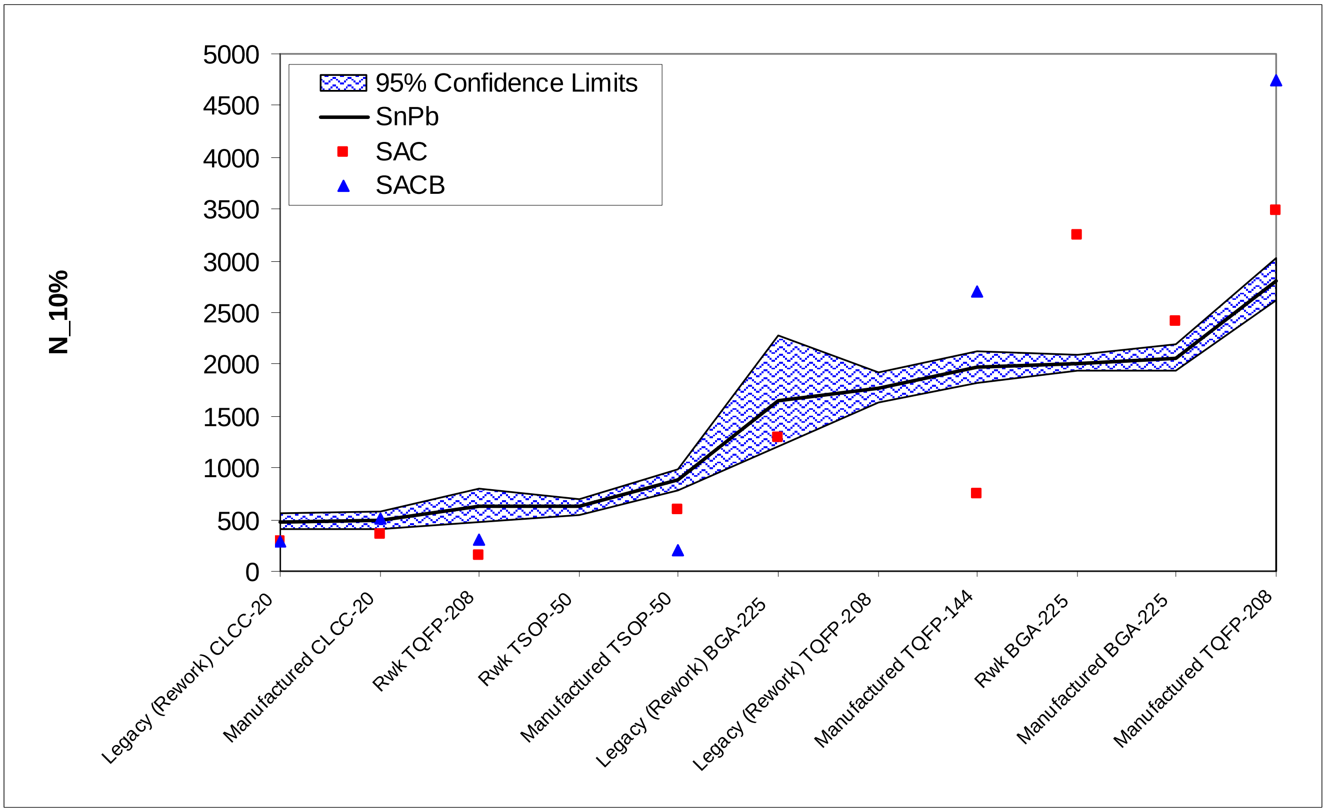

Figure 14 Lead-Free Compared to Tin-Lead Controls: 10% Failure Level in -55°C to +125°C Thermal Cycle Testing

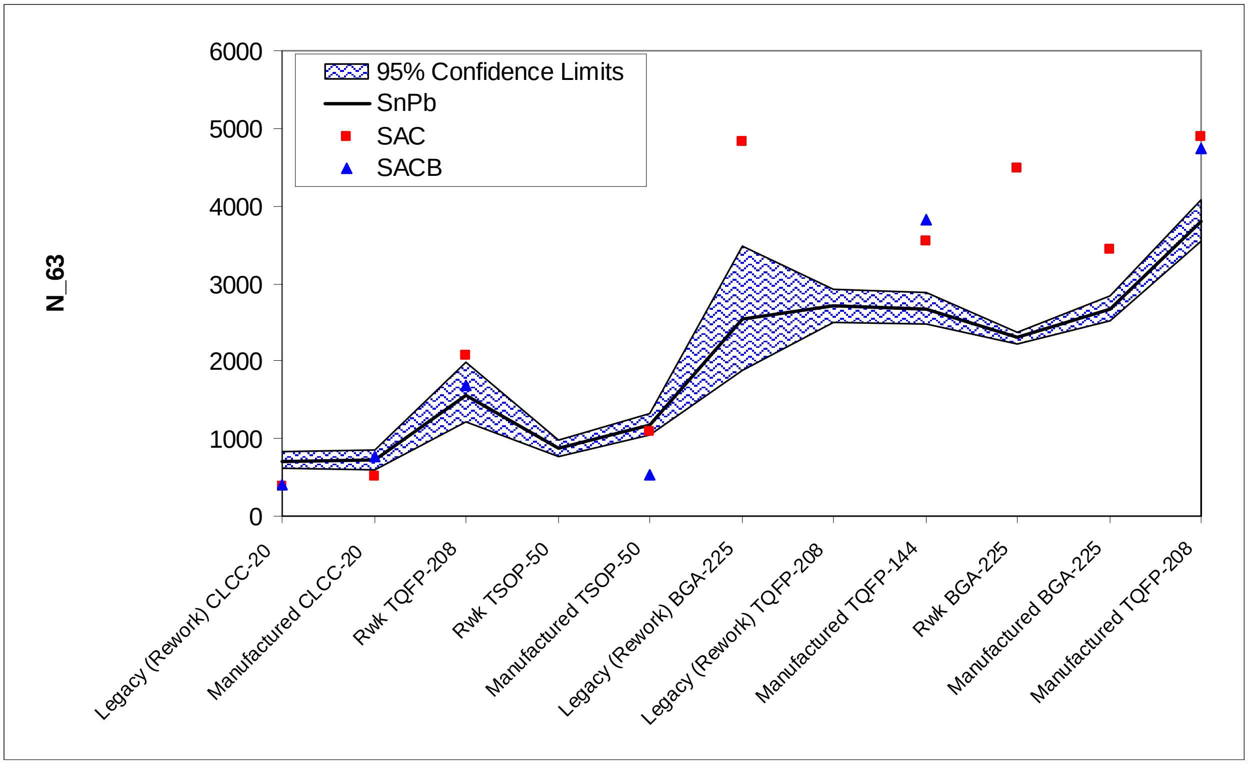

Figure 15 Pb-free Compared to Tin-Lead Controls: 63% Failure Level in -55°C to +125°C Thermal Cycle Testing

Table 22 N1/N10/N63 Solder Performance for -55°C to +125°C Thermal Cycle Testing

Solder Performance				
Component	**Solder/Finish**	**1st Failure**	**N10**	**N63**
BGA-225	SnPb/SnPb	1068	1822	2686
	SAC/SAC	533 (1100)	1248 (2394)	3675 (3447)
	SACB/SAC	2894	3123	4152
	SAC/SnPb	4 (229)	98 (321)	2743 (2113)
	SACB/SnPb	1536	1626	2560
CLCC-20	SnPb/SnPb	455	469	727
	SAC/SAC	288	358	510
	SACB/SACB	493	498	786
	SAC/SnPb	377	382	580
	SACB/SnPb	455	444	645
TQFP-144	SnPb/Sn	1473	1946	2681
	SAC/Sn	245	721	3626
	SACB/Sn	2605	2584	3988
TQFP-208	SnPb/ NiPdAu	1068	2138	3900
	SAC/ NiPdAu	704 (2833)	1696 (3484)	10029 (4907)
	SACB/ NiPdAu	506	*NF	*NF
TSOP-50	SnPb/SnPb	822	854	1192
	SAC/SnCu	440	634	1070
	SACB/SnCu	884	1179	1956
	SAC/SnPb	382	584	1096
	SACB/SnPb	157	173	570
Rwk BGA-225	NA/SnPb	1985	2006	2302
	NA/SAC	1 (3103)	23 (3175)	15245 (4521)
Rwk TQFP-208	SnPb/NiPdAu	533	603	1572
	SAC/NiPdAu	148	139	2167
	SACB/NiPdAu	1 (245)	1 (268)	652 (1775)
Rwk TSOP-50	SnPb/SnPb	305	241	584
	SAC/SnCu	534	627	1166
	SACB/SnCu	249	183	539

*NF = Not Enough Failures for the Generation of Weibull N10 and N63Values

(xxxx) = Indicate a Subject Data Interpretation due to Weibull Outlier Points

Table 23 Relative Solder Performance Comparison for -55°C to +125°C Thermal Cycle Testing

Relative Solder Performance				
Component	**Solder/Finish**	**1st Failure**	**N10**	**N63**
BGA-225	SnPb/SnPb	0	0	0
	SAC/SAC	+	++	++
	SACB/SAC	++	++	++
	SAC/SnPb	--	--	--
	SACB/SnPb	++	-	-
CLCC-20	SnPb/SnPb	0	0	0
	SAC/SAC	--	--	--
	SACB/SACB	+	+	+
	SAC/SnPb	-	-	--
	SACB/SnPb	0	-	-
TQFP-144	SnPb/Sn	0	0	0
	SAC/Sn	--	--	++
	SACB/Sn	++	++	++
TQFP-208	SnPb/ NiPdAu	0	0	0
	SAC/ NiPdAu	++	++	++
	SACB/ NiPdAu	--	++	++
TSOP-50	SnPb/SnPb	0	0	0
	SAC/SnCu	--	--	-
	SACB/SnCu	+	++	++
	SAC/SnPb	--	--	-
	SACB/SnPb	--	--	--
Rwk BGA-225	NA/SnPb	0	0	0
	NA/SAC	++	++	++
Rwk TQFP-208	SnPb/NiPdAu	0	0	0
	SAC/NiPdAu	--	--	++
	SACB/NiPdAu	--	--	--
Rwk TSOP-50	SnPb/SnPb	0	0	0
	SAC/SnCu	++	++	++
	SACB/SnCu	-	--	-

Legend:
0 = Same as control or <5% difference; + = 5 to 20%; ++ = >20%; - = -5 to -20%; -- = >-20% (red if much greater than -20%); NA = Not Available (not enough failures); NT = Not Tested; P = Pending (awaiting data)

4.6 Thermal Cycle -20°C to +80°C Test

4.6.1 Thermal Cycle -20°C to +80°C Test Method

This test determined solder joint reliability under thermal cycling conditions. This test was performed in accordance with IPC-SM-785 *(Guidelines for Accelerated Reliability Testing of Surface Mount Solder Attachments)* and Table 24. The project technical representatives from AMCOM noted that they required enough temperature cycles to produce sufficient failures for statistical analysis. In addition, two temperature cycles were required in order to define acceleration factors to allow extrapolation of the data to their systems' actual use conditions. AMCOM proposed temperature-cycling ranges of -55°C to +125°C and -20°C to +80°C.

Although 1,000 temperature cycles may be enough for some Programs to certify a product, this will not result in enough component failures for valid statistical analysis.

After examining the available data on dwell time effects, the Pb-free solder project participants reached agreement that the high-temperature dwell time for the -20°C to +80°C and -55°C to +125°C thermal cycles would be 30 minutes. Solder alloy creep during the high temperature dwell of the thermal cycle is a large contributor to the accumulated damage within the solder joints. In order to maximize the effects of solder alloy creep, a 30-minute high temperature dwell was used for this project.

Table 24 Thermal Cycling Test Methodology; -20°C to +80°C

Parameters, Manufactured PWAs	• -20°C to +80°C • Cycles: Until 63% failures or greater • Decision point at 5000 cycles if 63% failure not yet achieved • 5 to 10°C/minute ramp • 30 minute high temperature dwell • 10 minute low temperature dwell
Number and Type of Specimens	5 PWAs per solder alloy
Trials per Specimen	1
Acceptance Criteria	Electrical reliability better than or equal to tin/lead controls

4.6.2 Results for Thermal Cycle -20°C to +80°C Testing

This test is ongoing. At the end of July 2005, 5500 cycles had been accumulated. The CLCC-20s and TSOP-50s were the only component types to show significant failures at that point. It is estimated that between 10,000 and 15,000 cycles will be needed to fail the BGA-225 components (estimated test completion date is October 2006).

Based solely on the CLCC-20 failures, SACB is much more reliable than SAC which in turn is more reliable than SnPb.

The TSOP-50 data shows that SACB and SAC have equivalent reliability and both are more reliable than SnPb.

Contamination of Pb-free TSOP-50 solder joints with small amounts of lead (3%) resulted in a large decrease in the reliability of SACB but only a small decrease in the reliability of SAC. This negative effect of small amounts of lead on the reliability of bismuth-containing solders has been previously observed. To ensure maximum reliability, SACB solder should not be used when there is a chance that it may be mixed with SnPb solder.

The thermal cycle test results are summarized in Figure 16 and Table 25 and Table 26.

Figure 16 shows the Weibull N(10%) values for the different component/solder/finish combinations compared to the SnPb controls. The shaded area of the graph shows the 95% confidence intervals for the SnPb controls. Data within the bounded area indicate that the Pb-free soldered components have similar performance to the SnPb controls. Data outside the bounded area indicate the Pb-free soldered components have significantly different (better or worse) performance compared to the SnPb controls.

Table 25 shows the solder joint first failure numbers and the Weibull N(10%) and N(63%) numbers.

Table 26 shows the relative ranking of the solders for each component type based on the first failure, Weibull N(10%), and Weibull N(63%) numbers.

Table 27 lists the component/Pb-free solder/finish combinations that met the JTP acceptance criteria of solder joint reliability better than or equal to the eutectic SnPb controls (when comparing the ten percent Weibull cumulative failure numbers).

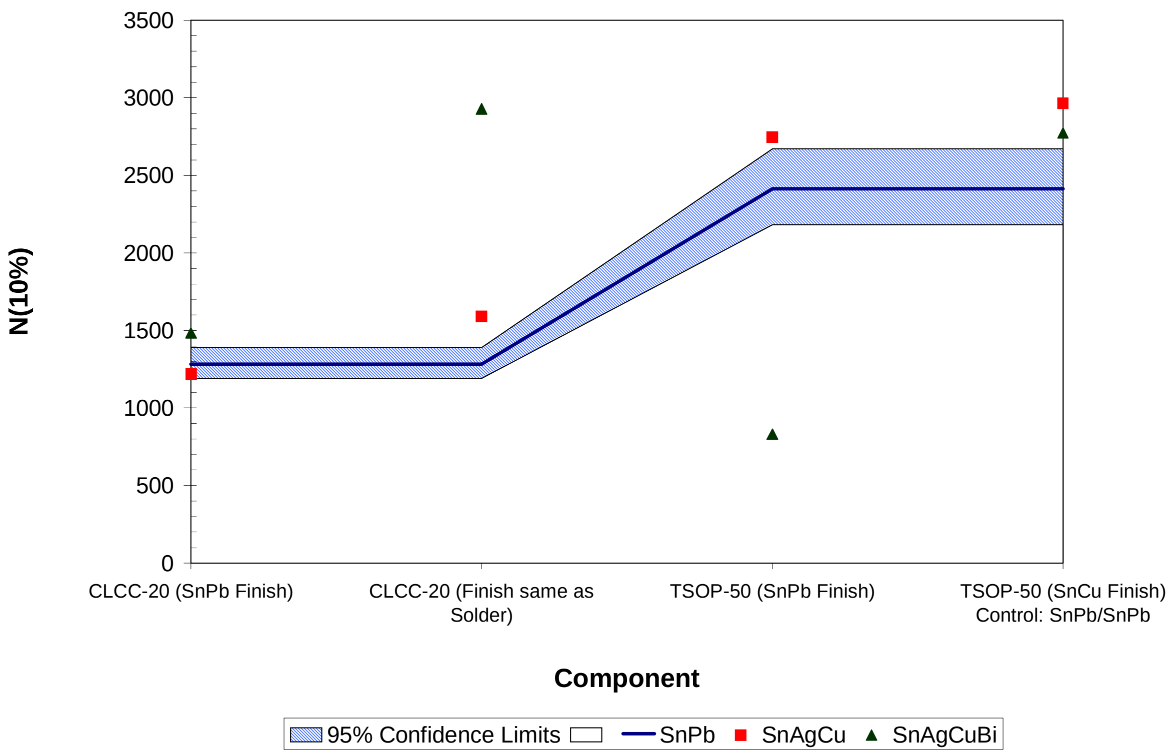

Figure 16 Pb-free Solders Compared to Tin Lead Controls Based on Weibull N(10%), ("Manufactured" and "Rework" -20°C to +80°C Thermal Cycle Test Vehicles)

Table 25 Weibull Numbers from the -20°C to +80°C Thermal Cycle Test, "Manufactured" Test Vehicles

Solder Performance -20 to +80°C Thermal Cycle "Manufactured" Test Vehicles				
Component	**Solder/Finish**	**1st Failure**	**N10**	**N63**
CLCC-20	SnPb/SnPb	1235	1282	1671
	SAC/SAC	1447	1590	2360
	SACB/SACB	2734	2929	3814
	SAC/SnPb	1227	1220	1721
	SACB/SnPb	1313	1484	1951
TSOP-50	SnPb/SnPb	2267	2413	3150
	SAC/SnCu	2636	2965	4141
	SACB/SnCu	2374	2773	4025
	SAC/SnPb	2393	2745	3513
	SACB/SnPb	805	832	1281

Table 26 Relative Solder Performance During -20°C to +80°C Thermal Cycle Testing "Manufactured", Test Vehicles

Relative Solder Performance -20 to +80°C Thermal Cycle "Manufactured" Test Vehicles				
Component	**Solder/Finish**	**1st Failure**	**N10**	**N63**
CLCC-20	SnPb/SnPb	0	0	0
	SAC/SAC	+	++	++
	SACB/SACB	++	++	++
	SAC/SnPb	0	-	0
	SACB/SnPb	+	+	+
TSOP-50	SnPb/SnPb	0	0	0
	SAC/SnCu	+	++	++
	SACB/SnCu	0	+	++
	SAC/SnPb	+	+	+
	SACB/SnPb	--	--	--

0 = Same as Control (5% or less difference)

Table 27 -20°C to +80°C Thermal Cycle Test Samples Meeting the JTP Acceptance Criteria

Test Vehicle	Solder Alloy	Component Finish	Component Type
"Manufactured"	SnAgCu	SnAgCu	CLCC-20
"Manufactured"	SnAgCuBi	SnAgCuBi	CLCC-20
"Manufactured"	SnAgCuBi	SnPb	CLCC-20
"Manufactured"	SnAgCu	SnCu	TSOP-50
"Manufactured"	SnAgCuBi	SnCu	TSOP-50
"Manufactured"	SnAgCu	SnPb	TSOP-50

4.7 Salt Fog Test

4.7.1 Salt Fog Test Method

This test determined the effects of salt fog on the physical and electrical aspects of Pb-free solder joints. This test was performed in accordance with MIL-STD-810F, Method 509.4 (Salt Fog).

Project technical representatives from the Air Force F-15 program and Naval Air Warfare Center Weapons Division require salt fog per MIL-STD-810F, Method 509.4 (Salt Fog) (or equivalent) because this test simulates the coastal atmosphere to which U.S. Air Force and Navy aircraft are subjected. The salt fog test validates the effect/non-effect of corrosion on the external package elements (leads). This has both a mechanical and electrical effect.

Table 28 Salt Fog Methodology

Parameters	• 5% +/- 1% salt solution concentration • Four 24 hour periods (two wet and two dry) • Exposure zone temperature 35°C +/- 2°C
Number and Type of Specimens	3 PWAs per solder alloy
Trials per Specimen	1
Acceptance Criteria	Performs better than or equal to tin/lead controls

4.7.2 Results for Salt Fog Testing

The PWAs were exposed to a 48 hour salt fog as per ASTM B117. Of the 9 boards tested, 2 boards had 3 component failures. All failures were attributed to packaging or wiring defects not related to the salt fog testing. Therefore, the SAC solder joints and the SACB solder joints were considered equivalent to the SnPb solder joints.

4.8 Humidity Test

4.8.1 Humidity Test Method

This test determined a test specimen's resistance to the deteriorative effects of high humidity and heat conditions. This test was performed in accordance with MIL-STD-810F, Method 507.4 (Humidity).

Project technical representatives from the Air Force F-15 program and Naval Air Warfare Center Weapons Division require humidity testing per MIL-STD-810F, Method 507.4 (Humidity) (or equivalent). The humidity (moisture resistance) test was required to evaluate, in an accelerated manner, the effect of high humidity and high temperature environments (i.e., tropical environment) on the Pb-free solder joint appearance.

Table 29 Humidity Test Methodology

Parameters	• Five 48-hour cycles per Figure 507.4-1 in MIL-STD-810F, Method 507.4 (Humidity)
Number and Type of Specimens	3 PWAs per solder alloy
Trials per Specimens	1
Acceptance Criteria	Performs better than or equal to tin/lead controls

4.8.2 Results for Humidity Testing

The PWAs specified were exposed to 30°C and 95% Relative Humidity (RH) for five 48-hour cycles per MIL-STD-810F, Method 507.4. Of the 9 boards tested, 2 boards had 1 component failure. Failure analysis determined that the component failures were attributed to packaging or wiring defects and not related to the temperature humidity testing performed. Therefore, the Pb-free SAC solder joints and the SACB solder joints were considered equivalent to the SnPb solder joints.

4.9 Surface Insulation Resistance (SIR) Test

4.9.1 Surface Insulation Resistance (SIR) Test Method

Surface insulation resistance and electrochemical migration resistance test methodologies are used to characterize the propensity for a material system to exhibit electrochemical failure mechanisms, such as leakage currents under humid conditions, electrolytic corrosion, and electrochemical migration (dendritic growth). Both methodologies involve subjecting a processed test substrate to elevated levels of temperature and humidity under the influence of an electrical potential, and examining the changes in measured resistance across standard test patterns. The overall level of the measured resistance, as well as the trends with time in test, allow a trained professional to assess the risk of electrochemical failure for a given set of material and process conditions. A visual examination of the test patterns following the temperature-humidity exposure provides additional insight into the potential corrosive nature of residues remaining from a manufacturing process. IPC-9201, The SIR Handbook, contains more tutorial information on these test methodologies.

It is critical to understand that SIR and electrochemical migration resistance test methodologies examine systems of materials and the manufacturing processes used to produce the samples, not the materials alone.

<u>Test Vehicle</u>

The test vehicle for this evaluation was the IPC-B-24 standard test board. This is the qualification vehicle for fluxes and solder pastes per IPC-J-STD-004. The test vehicles were fabricated from 0.060 inch FR-4 epoxy glass laminate with bare copper finish. This is the standard board condition for J-STD-004 flux qualification. The B-24 board has four interdigitated comb patterns, with 0.016 in lines and 0.020 in spaces.

Test Profile

The SIR test method for this evaluation was a variation of IPC-TM-650, method 2.6.3.3, which is the SIR test method specified by J-STD-004 and has been used for many years in the industry. This method involves exposure of the processed test samples to 168 hours of 85°C / 85% relative humidity (RH), with a bias of 50 volts DC applied to all comb patterns throughout the test. Bias is not applied during temperature-humidity ramp up or ramp down portions of the test. Normally, SIR measurements are taken at (1) initial ambient; (2) 24 hours; (3) 96 hours; (4) 168 hours; and (5) final ambient. Measurement voltage was 100 volts DC.

For this evaluation, measurements were taken at (1) initial ambient; (2) 72 hours; (3) 120 hours; and (4) 168 hours. A minimum acceptable insulation resistance of 10^8 ohms (100 megohms) was defined for this evaluation. SIR testing was performed by Boeing at the Anaheim facility.

Following the SIR test, the boards were visually examined by Rockwell Collins, using both standard lighting (to look for corrosion) and back lighting (to look for dendritic growth). Digital images were recorded of all observed phenomena. A visual ranking scale was also developed to illustrate the degree of corrosion or the degree of electrochemical migration. Analysis and interpretation of the SIR data was also performed by Rockwell Collins.

Eight process groups were evaluated as shown in the Table 30.

Table 30 Surface Insulation Resistance Test Methodology

Parameters	• 85°C +/- 2°C at 85% +/- 2% relative humidity for 168 hours.
Number and Type of Specimens	IPC-B-24 boards 6 – Boards with bare copper finish[1], no solder paste, only processed through cleaning procedures – Group 1 5 – Boards with bare copper finish[1], no solder paste, passed through reflow and wave solder machines then cleaned – Group 2 6 – Boards with SnAgCu[2] reflow solder alloy and flux – Group 3 6 – Boards with SnAgCuBi[3] reflow solder alloy and flux – Group 4 6 – Boards with SnPb[4] reflow solder alloy and flux – Group 5 6 – Boards with SnCu[5] wave solder alloy and flux – Group 6 6 – Boards with SnAgCu[6] wave solder alloy and flux – Group 7 6 – Boards with SnPb[7] wave solder alloy and flux – Group 8
Trials per Specimen	1
Acceptance Criteria	$\geq 10^8\ \Omega$

[1] Controls
[2] ECO Solder 7100-GRN360K paste and Senju ROL1 flux
[3] Heraeus CL30-8467 paste with RMA flux
[4] Sn37pB Kester 244 paste with Kester ROL0 flux
[5] SnCu SN100, Nihon Superior alloy, Alpha Metals NR310B VOC-free low solids flux
[6] Kester E-Bar Sn95.8Ag3.5Cu0.7 alloy, Alpha NR310B VOC-free low solids flux
[7] Sn37Pb Kester Ultra Pure alloy, Alpha Metals NR310 VOC-free low solids flux

All test boards were cleaned using Kyzen Ionox I3330 semi-aqueous cleaning chemistry.

The cleaned controls were included to examine the effects of the cleaning process on the test vehicle, without the complicating factors of flux residues.

The heated controls were included to examine the effects of the reflow and cleaning processes, without the complicating factors of flux residues.

4.9.2 **Results for Surface Insulation Resistance (SIR) Testing**

The SIR data is shown in the form of boxplots, or box and whisker plots. This gives a graphical representation of the level of the measured SIR, as well as the relative distribution of the data sets. The line in the center of each box represents the median value (half the data above this point, half below). The width of the box and end of each whisker represent the 95% confidence interval for that data population. Circles and asterisks represent values which the statistical software (Systat) considers to be outliers. The Y axis in each graph is represented in LogOhms, which is the base 10 logarithm of the measured resistance. A value of 7.0 equals 10 megohms, 8.0 equals 100 megohms (1E+8 ohms), and so on. For this evaluation, the minimum acceptable SIR level is 100 megohms or 8.0 LogOhms.

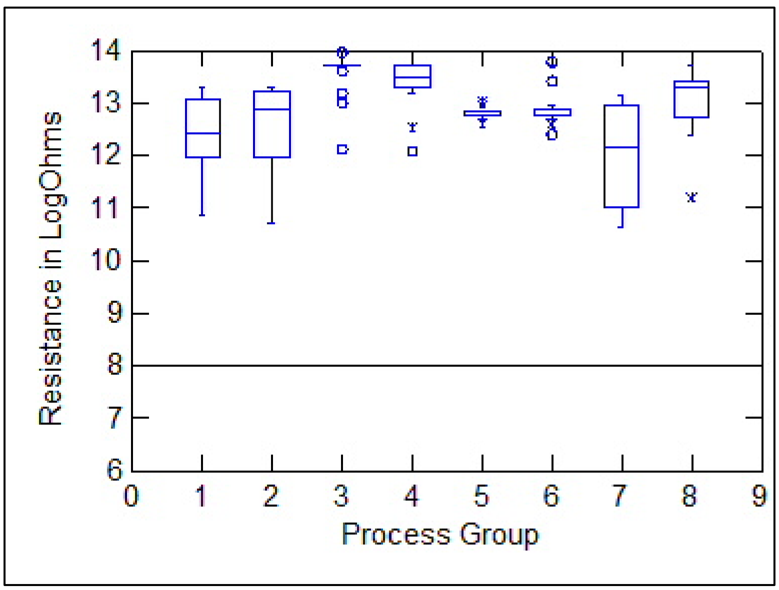

Figure 17 Initial SIR Levels – Ambient Conditions

In Figure 17, all of the initial SIR levels at ambient conditions are relatively high and exhibit an acceptable initial cleanliness levels. In general, values under 11.0 LogOhms are undesirable. Groups 1 and 2 represent the bare copper controls. Such a spread of data is considered typical for bare copper controls, both heated and cleaned. Judgments of the “worth” of the candidate processes should not be based on the initial ambient values. The spread of the various data groupings relative to each other is considered typical for B-24 coupon evaluations.

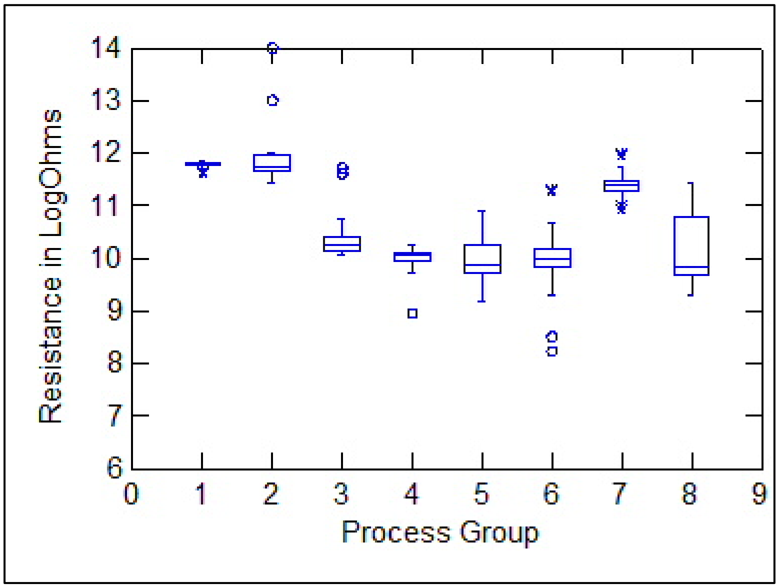

Figure 18 SIR Levels at 72 Hours – 85°C / 85% RH

Figure 18 shows the SIR levels after 72 hours at elevated temperature and humidity conditions. Both the heated controls and the cleaned controls show high measured values, indicating that the test was being run properly. Had there been a problem with the chamber control or the environment at the time of measurement, the values would have been lower. All of the measured data points were above the 100 megohm (8.0 LogOhms) limit and so were numerically acceptable. For this figure, higher levels and tighter distributions should be considered as desirable.

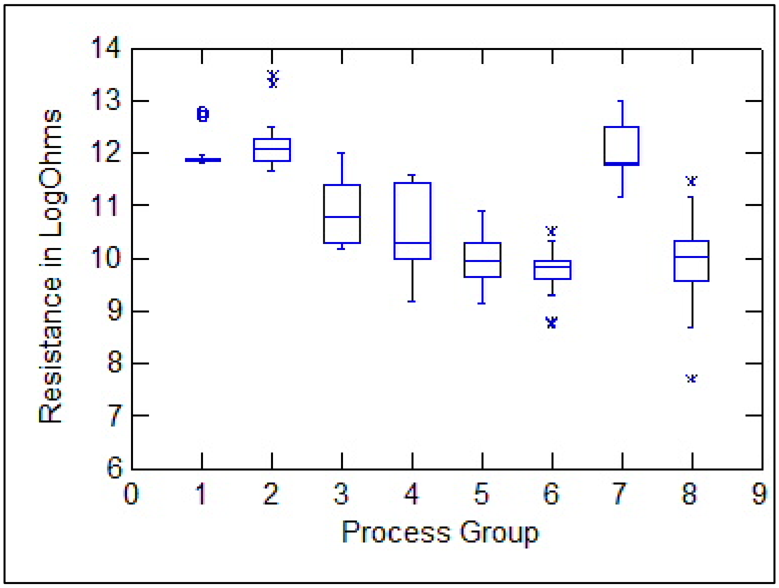

Figure 19 SIR Levels at 120 Hours – 85°C / 85% RH

Figure 19 shows the measured resistances at 120 hours of elevated exposure. In this data set, Group 8 (SnPb Wave) had the only measured resistance under 100 megohms. Of the three solder paste groups (3-5), the SAC group had the highest overall levels, with SnPb being the lowest group. Of the wave solder groups (6-8), the SAC Wave had the highest observed level, and SnPb Wave the lowest.

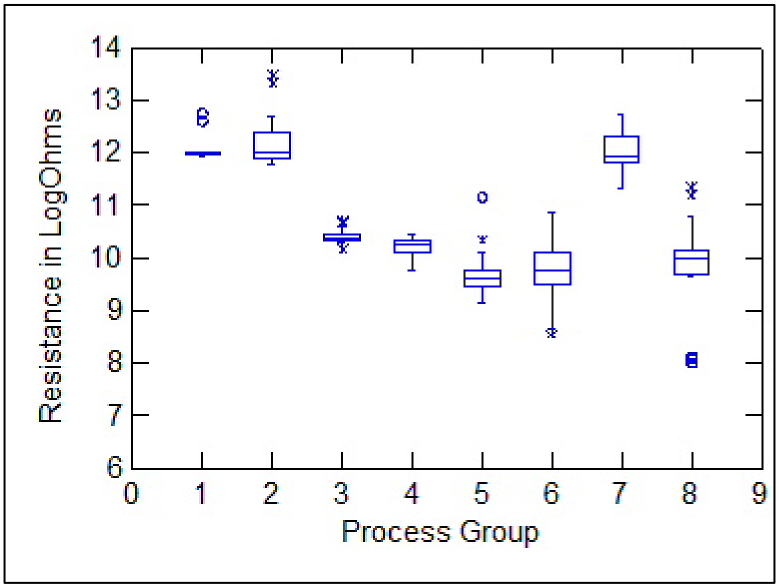

Figure 20 SIR Levels at 168 Hours – 85°C / 85% RH

Figure 20 shows the resistance levels after one week of elevated exposure. All of the measured resistances were above the 100 megohm numerical limit. The same judgments can be made as for the 120 hour readings. The distributions have grown tighter, but this is typical after long term exposure to elevated temperature and humidity conditions.

SIR Visuals

Both the heated controls and the cleaned controls had no dendritic growth. The change in appearance of the copper electrodes was judged to be normal oxidation.

All of the test electrode patterns had some form of oxidation or corrosion by-product on the surface. Much of the oxidation or change in visual appearance is standard for this type of test and for this test board. None of the test groups emerged from the SIR test with clean patterns free from dendritic growth.

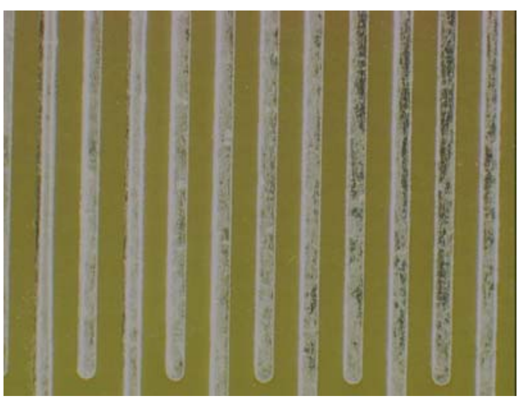

Figure 21 Normal oxidation of soldered patterns

The control coupons had no dendritic growth or corrosion, indicating that there were no irregularities with the chamber control or chamber temperature-humidity profile. The test measurements were not taken exactly as specified by J-STD-004 or in IPC-TM-650, method

2.6.3.3. To run the test per these specifications, the measurements would have to be taken at 24, 96, and 168 hours, with a final ambient reading taken 1-2 hours after the chamber had returned to ambient conditions. Therefore, the test results should be viewed as a "first approximation".

The presence of the dendrites and some of the corrosion byproducts indicate that the manufacturing process was not optimized for flux removal, at least for these test samples and how they were processed. It should be noted that no corrosion or dendritic growth was noted on any of the other test substrates (not SIR and not EMR) when exposed to MIL-STD humidity testing.

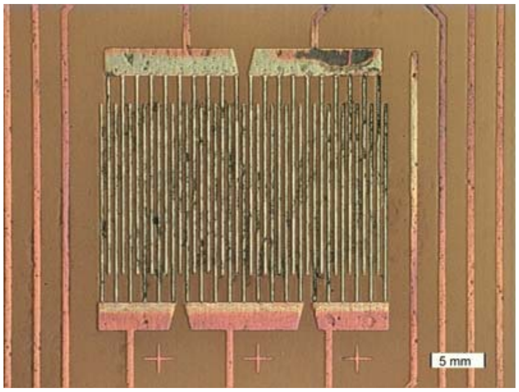

Figure 22 Tin-silver-copper-bismuth reflow with black corrosion and light-colored contamination after SIR testing

4.10 Electrochemical Migration Resistance (EMR) Test

4.10.1 Electrochemical Migration Resistance (EMR) Test Method

Electrochemical migration resistance testing is similar in nature to SIR testing, with the application of an electrical potential to a test pattern exposed to elevated temperature and humidity. The EMR test method chosen was IPC-TM-650, Method 2.6.14.1 (Electrochemical Migration Resistance Test), which is equivalent to the venerable Bellcore electromigration test method.

Table 31 Electrochemical Migration Resistance Test Methodology

Parameters	85°C +/- 2°C at 88.5% +/- 3.5% RH
Number and Type of Specimens	IPC-B-25A boards with D-comb pattern 6 – Boards with SnAgCu reflow solder alloy and flux 6 – Boards with SnAgCuBi reflow solder alloy and flux 6 – Boards with SnPb reflow solder alloy and flux 6 – Boards with SnCu wave solder alloy and flux 6 – Boards with SnAgCu wave solder alloy and flux 6 – Boards with SnPb wave solder alloy and flux 6 – Boards with bare copper finish, no solder paste, only processed through cleaning procedures 5 – Boards with bare copper finish, no solder paste, passed through reflow and wave solder machines then cleaned
Trials per Specimens	1
Acceptance Criteria	• $IR_{final} \geq (IR_{initial})/10$, that is the average insulation resistance shall not degrade by more than one decade as a result of the applied bias. • No evidence of electrochemical migration (filament growth) that reduces the conductor spacing by more than 20% • No corrosion of the conductors; minor discoloration of one polarity of the comb pattern conductors is normal.

4.10.2 **Results for Electrochemical Migration Resistance (EMR) Testing**

EMR was performed per IPC-TM-650 2.6.14.1., 65° C, 85% RH, 100VDC, 96 hrs unbiased, 500 hrs biased (596 hrs total). The test vehicle used was the IPC-B-25A Standard Test Board, Comb D. Comb D is a 5-point test pattern with 12.5 mil lines and spaces.

<u>Reflow solder</u>

- SnAgCu solder alloy ECO Solder 7100-GRN360K and no-clean flux Senju ROL1
- SnAgCuBi solder alloy Haraeus CL30-8467 and no-clean flux RMA
- Sn37Pb Kester R244 solder alloy and flux Kester ROL0

<u>Wave solder</u>

- SnCu SN100C, Nihon Superior NR310B, Alpha VOC-Free no-clean flux
- SnAgCu (Kester) E-Bar Sn 95.8Ag3.5Cu.7 flux NR310B Alpha
- Sn37Pb Kester Ultra Pure and NR310 Alpha Type ORM0 flux

Control coupons were bare copper finish boards processed to simulate reflow, wave solder, and cleaning procedures only. All coupons were cleaned with semi-aqueous process using IONOX I3330.

EMR Numericals

Table 32 Selected EMR Values

S/N	Initials	96 Hrs	Dendrites 10x
SN AG CU BI CL30-8467			
SABC 1	1.5 +E11	1.3+E8	Y
SABC 2	1.0 +E11	1.3+E8	Y
SABC 3	4.1 +E10	1.0+E8	N
SABC 7	9.5 +E10	8.5 +E7	Y
SABC 5	1.4 +E11	1.7+E8	N
SABC 6	3.8 +E10	1.25+E8	Y
SN CU SN100C			
SCW 1	1.8 +E11	1.2 +E7	N
SCW 2	8.0 +E9	6.5+E6	N
SCW 3	1.05 +E11	4.5 +E7	Y
SCW 4	8.5 +E9	9.2+E6	N
SCW 5	1.8 +E11	1.25 +E9	N
SCW 6	1.4 +E11	7.0 +E7	N
SN PB KESTER R244			
1	2.6 +E11	3.5 +E10	N
2	2.6 +E11	1.2 +E9	N
5	2.4 +E11	9.0 +E9	N
9	2.6 +E11	2.1+E8	N
8	2.6 +E11	2.2+E8	N
6	2.6 +E11	1.5 +E9	Y
SN AG CU 7100 GNR 360 K			
SACU 11	2.6 +E11	2.0+E8	Y
SACU 9	1.8 +E11	4.1 +E7	N
SACU 3	3.2 +E11	1.15 +E9	Y
SACU 12	2.4 +E11	5.8+E8	N
SACU 16	2.6 +E11	2.8+E8	N
SACU 4	2.4 +E11	3.8 +E9	Y

Table 32 shows initial ambient resistance values, which would generally be considered as acceptable; however, the values at the 96 hour mark are generally low for a number of test patterns. The EMR test methodology does not specify a minimum insulation resistance value for any measurement, only that the final measurement cannot be more than a decade lower than the initial. This is one of the shortcomings of this test method. While acceptable per the test method, the overall levels should be in the high 1E+08 or higher range. Table 32 also shows whether or not dendrites were noted on that test pattern after the test. In many cases, a low measured resistance does not predict the development of dendritic growth.

Post EMR Visual Examination

Appearance after testing was:

- Tin-silver-copper reflow and wave soldered with 7100 GNR 360K had the fewest dendrites and corrosion.
- Tin copper had light-colored contamination and dendrites. See Figure 23.
- Tin-silver-copper-bismuth reflow had black corrosion and light-colored contamination between traces. Solder exhibited poor wettability. A more active flux may help. See Figure 24.

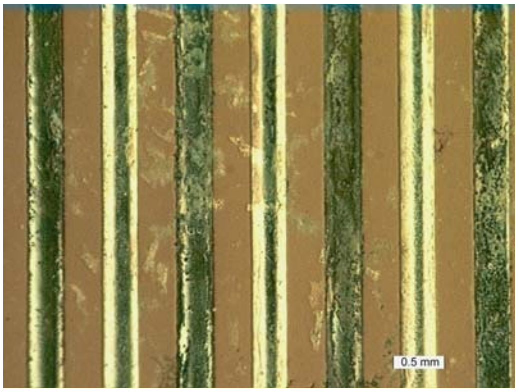

Figure 23 Tin-copper with light-colored contamination and dendrites

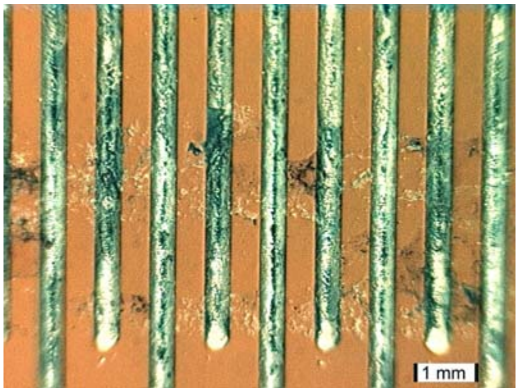

Figure 24 Tin-silver-copper-bismuth reflow with black corrosion and light-colored contamination after EMR testing

5 Test Result Discussions

5.1 Test Vehicle Build

Pb-free reflow soldering is a very different process than SnPb reflow soldering because the full liquidus temperature is approximately 38 degrees higher but the part and board thermal properties have not changed.

Visual examination of Pb-free reflowed solder joints, in some cases is not a good indicator of acceptable reflow because, depending on the alloy used, the joints will not be as shiny or may have a grainy appearance. Because visual examination is not always a good indicator of reflow, it may be necessary to rely on the reflow profile to assure reflow.

It may be necessary to change fluxing parameters to improve flux function.

Rework is different for Pb-free solder alloys because of the higher temperatures required. Caution is required to assure that components do not exceed their allowable temperature. Continuity testing, X-ray and endoscopic inspection should be performed on each reworked BGA-225.

Higher tip temperatures (700°F) are required for Pb-free hand soldering. Because of the higher temperature and longer dwell time, it is easy to lift pads during hand soldering. Because the higher temperatures used during soldering will do more oxidizing of the flux residue, cleaning under BGA-225s is more difficult.

Each Pb-free alloy/board finish combination has different wetting and spreading characteristics, so inspectors will require additional training.

5.2 Vibration Test

The results of the vibration test suggest that for some component types, Pb-free solders are as reliable as the currently used eutectic SnPb solder.

Unfortunately, this study also demonstrated that with other component types, the Pb-free solders failed before the SnPb control. Although this does not mean that Pb-free solders can not be used in high-performance electronics, it does imply that models for calculating the actual field lifetime of Pb-free solder joints on certain component types will need to be developed and validated using actual vibration test data (from this and other studies). These models can then be used to verify that electronics made with Pb-free solders will survive for the required lifetime in the field.

5.3 Mechanical Shock Test

Mechanical shock test procedure 1, all alloys passed the environmental stress screening test described in MIL-STD 810F; Method 516.5; Procedure 1. The SnPb and SAC soldered assemblies did not have any failures. The SACB soldered assemblies had three (3) TQFP-208 components and one (1) TSOP-50 component which failed.

The results from mechanical shock test procedure 2 were inconclusive. At the lower shock levels (< 100 G Peak), there was a minimum number of failures during the tests, so no definitive conclusions could be reached. Levels tested were consistent with the Function Test for Flight Equipment levels, the Function Test for Ground Equipment levels, and the Crash Hazard Test for Flight Equipment levels in mechanical shock test procedure 1. 100 shocks were given at each test level the Z-axis only. In mechanical shock test procedure 1, three (3) shocks were provided in each axis.

At the higher mechanical shock test procedure 2 test levels (> 100 G Peak), the data is inconclusive because the test set-up recorded simultaneous failures of multiple components. A detailed review of the raw test data within this range showed that failures were not related to the solder joints. Failure analysis concluded that SnPb and Pb-free solder joints survived the higher stress levels.

It was concluded that the false failures were due to discontinuities within the connector or at the board traces. Failures were found within the board copper traces at the land-trace interface area. Failure analysis on BGA-225 solder joint cross sections revealed that several BGA-225 solder balls had partially traversed cracks, but no complete failure.

5.4 Combined Environments Test

Additional statistical analysis was conducted using Statgraphics version 5 software. Variance component analysis was conducted on “Manufactured” test vehicle data. The analysis of variance table divides the variance of the cycles to failure into 5 components, one for each factor. The factors included: solder paste; lead finish; component location along the x-axis (long axis of the board); component location along the y-axis; component type; plus unexplained error. The analysis shows that solder joint reliability was influenced by the choice of solder paste, but it was probably less than either the choice of component or random noise. The random noise would include other factors not included in the experiment or analysis. The analysis further shows that the influence due to lead finish or component location is very low.

Overall, the component type had the greatest effect on solder joint reliability performance. The plated through-hole components proved to be more reliable than the surface mount technology components. The plated through-holes, PDIP-20 and PLCC-20 components performed the best. The reworked TSOP-50, CSP-100 and hybrid components had the worst solder joint reliability.

The solder alloy had a major effect on solder joint reliability. In general, SAC soldered components were less reliable than the SnPb soldered controls. In general, SACB soldered components were more reliable than the SnPb soldered controls with the exceptions of SnPb BGA-225 components, SnPb TSOP-50 components and reworked components due to the lead contamination in the solder joints.

The component location on the test vehicle in the x-axis (along the long dimension of the board) and lead finish had minor effect on solder joint reliability. The component location relative to the y-axis had no effect on solder joint reliability.

The effect of SnPb contamination on Pb-free solder joint reliability was analyzed by comparing Weibull plots of the SnPb and Pb-free components soldered with Pb-free solders.

- For BGA-225; the presence of SnPb appears to degrade the reliability of SAC solder while the presence of SnPb does not appear to have a significant effect on the reliability of SACB solder.
- For CLCC-20; the presence of SnPb appears to improve the reliability of the SAC solder while the presence of SnPb appears to degrade the reliability of the SACB solder.
- For TSOP-50; the presence of SnPb appears to slightly improve the reliability of the SAC solder while the presence of SnPb appears to severely degrade the reliability of the SACB solder.

Therefore, the degradation of SACB solder joint reliability due to SnPb component finish appears to be inversely proportional to the amount of SnPb finish on the component. Microsection analysis may reveal a bismuth-lead or other intermetallic compound that is formed in the presence of lower lead contamination levels and that reduces the overall solder joint reliability.

The Weibull plots for SnPb solder components on “Manufactured” test vehicles were plotted with the Weibull plots of the un-reworked SnPb soldered components on “Rework” test vehicles. The comparison was made to determine the effects of the differences in laminate materials and board surface finishes. The “Manufactured” test vehicle boards were fabricated from high glass transition temperature laminate with immersion silver surface finish. The “Rework” test vehicles were fabricated from relatively low glass transition temperature laminate with hot air soldered level surface finish. Overall, the controls on the “Manufactured” test vehicles were more robust than the corresponding controls on the “Rework” test vehicles. In general, the higher glass transition temperature laminate and immersion silver board surface finish appear to enhance the reliability of the SnPb solder joints.

5.5 Thermal Shock Test

Based solely on the data from the CLCC-20 failures, SnPb is more reliable than SACB which in turn is more reliable than SAC. This result does not necessarily mean that Pb-free solders should be restricted from use in high-performance electronics, but it does imply that models for calculating the actual field lifetime of Pb-free solder joints will need to be developed in order to verify that Pb-free solders will survive for the required lifetime of a given circuit assembly design.

In general, mixing SnPb and Pb-free solders resulted in reduced reliability. Also, reworking some component types gave reduced reliability (TSOP-50s and TQFPs).

A literature search was conducted to collect published Weibull parameters for SnPb and Pb-free solders (mainly SAC) used with various component types. The data from the literature search showed that SnPb solder outperforms SAC when the solders are used with components that have a large CTE mismatch with the printed wiring board laminate (e.g., CLCC-20s and Alloy 42 TSOP-50s) and tested using a thermal cycle with a large delta T (e.g., -55°C to +125°C). The assumption is that conditions that highly stress the solder joints by maximizing the CTE difference between the PWB and the component will favor SnPb over SAC. Conversely, conditions that minimize the stress put on the solder joints (e.g., compliant components such as BGA-225 and/or a thermal cycle with a small delta T) will favor SAC over SnPb.

In support of this assumption, J.P. Clech analyzed the available literature data and was able to demonstrate that with shear strains of greater than 6.2%, SnPb is more reliable than SAC while the reverse is true with lesser shear strains. The thermal shock cycle used for the current test produced strains greater than 6.2% for the CLCC-20s, which suggests that although SnPb solder outperformed the Pb-free solders in this highly accelerated test, the Pb-free solders will likely outperform SnPb solder under actual field conditions. This assumption is supported by the results of the -20° to +80°C thermal cycle test which produced much less stress in the solder joints than did the thermal shock test and which showed that Pb-free solders outperform SnPb.

Models need to be developed (and verified with actual thermal cycle test data from this study and other studies) which can be used to accurately predict field lifetimes for Pb-free solders used with different component types. A verified model will allow field lifetimes to be predicted for any component on any board design.

5.6 Thermal Cycle -55°C to +125°C Test

BGA-225 components: the Pb-free solder alloys had equal to or better thermal cycle performance than the SnPb solder alloy baseline for the matched solder alloy/component finish combinations. Mixed metallurgy solder alloy/component finish combinations such as SAC/SnPb or SACB/SnPb had degraded thermal cycle solder joint integrity in comparison to the SnPb solder alloy baseline solder joint integrity.

CLCC-20 components: the Pb-free solder alloys had lower solder joint thermal cycle performance in comparison to the SnPb solder alloy baseline except for the SACB/SACB solder alloy/component finish combination. The ceramic construction of the CLCC-20 component induced a higher CTE mismatch resulting in a high solder joint stress that impacted the Pb-free solder alloys to a greater extent than the SnPb solder alloy baseline.

TQFP-144 components: the SACB solder alloy had better performance than the SnPb solder alloy baseline. The SAC solder alloy had mixed performance results in comparison to the SnPb solder alloy baseline.

TQFP-208 components: the Pb-free solder alloys had equal to or better than thermal cycle performance in comparison to the SnPb solder alloy baseline solder joint integrity.

TSOP-50 components: the SAC solder alloy had lower performance in comparison to the SnPb solder alloy. The SACB solder alloy had better performance in comparison to the SnPb solder alloy except where a SnPb component finish was used. The SnPb component finish created a Pb contamination issue resulting in degraded solder joint integrity.

Rework practices: the rework aspects of the investigation produced mixed results, sometimes the Pb-free solder alloys had better performance and sometimes they had worse performance than the SnPb control.

Tin Whiskers: occurrences of both Sn and Pb whiskers were found on the thermal cycle test vehicles after the completion of 4743 total thermal cycles. The TSOP-50 components were the primary whisker generators. The Sn plated TQFP-144 components were observed to have sporadic tin whisker occurrence. The Sn plated PDIP-20 and PLCC-20 components were not observed to have any tin whiskers. None of the whiskers observed violated minimum electrical spacing dimensions.

The SACB solder alloy thermal cycle solder joint integrity was significantly impacted by SnPb component finish combinations.

Solder joint – intermetallic interface voiding: no Kirkendall voiding was observed at the solder joint/intermetallic interface after the accumulation of a total of 2372 hours at +125°C during the thermal cycle testing.

Solder Joint Shrinkage Voids and Fillet Lifting: No thermal cycle failures were observed due to the presence of solder joint shrinkage voids or fillet lifting phenomena.

5.7 Thermal Cycle -20°C to +80°C Test

Based solely on the data from the CLCC-20 and TSOP-50 failures, the Pb-free solders are more reliable than SnPb. This result conflicts with the thermal shock data which shows just the reverse.

Again, the assumption is that conditions that highly stress the solder joints by maximizing the CTE difference between the PWB and the component will favor SnPb over SAC. Conversely, conditions that minimize the stress put on the solder joints (e.g., compliant components such as BGAs and/or a thermal cycle with a small delta T) will favor SAC over SnPb. We can also say with some confidence that the Pb-free alloys will outperform SnPb under field conditions that are less stressful than the -20°C to +80°C thermal cycle test.

Models need to be developed (and verified with actual thermal cycle test data from this study and other studies) which can be used to accurately predict field lifetimes for Pb-free solders used with different component types. A verified model will allow field lifetimes to be predicted for any component on any board design.

5.8 Salt Fog Test

Nine boards were subjected to salt fog testing. After exposure, all components on all boards were tested for continuity. Board 104 SAC/SAC had two (2) component failures and Board 105 SAC/SAC had one (1) component failure. The following is the results of failure analysis on the components:

Board 104: Component U35 (PDIP-20): Open circuits where the component leads were supposed to be in series (daisy chained).

Board 104: Component U56 (BGA-225): Continuity testing showed that there was an open circuit within the component.

Board 105: Component U3 (TQFP-208): There was a resistance reading of 70.6 Ohms across the terminals of the component indicating an improperly wired component.

All of these failures were packaging failures that could not be caused by salt fog testing. All components and boards passed the test.

Therefore, based on the salt fog testing performed, SAC, SACB, and the SnCu Pb-free solder joints reliability are equivalent to SnPb solder joints.

5.9 Humidity Test

In the humidity tests, 9 boards were tested. After exposure, all components on all boards were tested for continuity. Board 38 SnPb/SnPb and Board 108 SAC/SAC each had a component which failed. Failure analysis revealed the following results:

Board 38: Component U49 (PDIP-20): The open circuit was caused by a broken bond within the chip.

Board 108: Component U44 (BGA-225): Continuity testing showed that there is an open within the component.

Both failures could not be attributed to the solders used. They were deemed manufacturing failures from the component manufacturer. The balance of components passed humidity and continuity testing.

Therefore, based on the humidity test results, it was concluded that SAC, SACB, and the SnCu Pb-free solder joints reliability are equivalent to SnPb solder joints.

5.10 Surface Insulation Resistance (SIR) and Electrochemical Migration Resistance (EMR) Tests

Dendritic growth and oxidation/corrosion were noted for all of the candidate flux and paste combinations in both the SIR and EMR tests. The absence of dendritic growth and corrosion on the control boards indicates that the chamber was under proper control for these tests, although there were some irregularities in the measurement timing for the SIR test.

Of the three alloys tested (tin-silver-copper, tin-copper, and tin-silver-copper-bismuth), tin-silver-copper and tin-copper performed as well or better than tin-lead alloys. The tin-silver-copper and tin-copper alloys both used NR310B VOC-free no-clean flux.

The tin-silver-copper-bismuth, which used a Heraeus no-clean RMA flux, developed black spots on the solder during EMR and SIR testing. The discoloration appears to be corrosion, which may be a result of flux residues left after cleaning.

Some kind of cleanliness evaluation/ comparison such as ion chromatography could be added to similar process evaluations to measure contaminants before environmental testing and develop a correlation between the residues remaining after cleaning and their effect on electrical performance.

Light colored residues were noted on some of the test specimens, which may be oxidation or flux residues remaining after cleaning.

No significant correlation could be drawn between resistance measurements in these tests and the presence of corrosion or dendritic growth on the comb patterns.

There are no "good" or "bad" materials and the results of the SIR or EMR tests should not be viewed in this manner. The only valid conclusion from either the SIR or EMR tests are that the manufacturing processes were not optimized for flux removal for these test vehicles. The same can be said of any manufacturing process. It should be noted that no corrosion or dendritic growth was found on any of the other humidity-based tests in this study, where manufacturing processes were more realistic.

6 Summary Tables

Table 33 and Table 34 provide a qualitative comparative summary of the relative performance of the Pb-free solder alloys based on 10 % Weibull failure numbers. Table 33 is for "Manufactured" and "Hybrid" test vehicles and Table 34 is for "Rework" test vehicles. All comparisons are based on a two-parameter Weibull analysis of the data for the thermal cycle tests (both temperature ranges), combined environments test, and thermal shock test. Mechanical shock and vibration data are not included in the tables because Weibull analysis was not considered appropriate.

Baseline SnPb data and other solder alloy/component finish data which is within 5% of the baseline is denoted with a 0. Single symbols, – or +, denote data that is 5% to 20% above (+) or below (-) the baseline. Double symbols, -- or ++, denote data that is more than 20% above (++) or below (--) the baseline. Green cells denote performance better than the SnPb baseline. Yellow cells denote performance worse than the SnPb baseline. Red cells denote data that is grossly worse than the SnPb baseline. Numerical values can be found in the "Weibull Numbers" Tables. Testing still in-progress is denoted with a P. Data that is not available or where there were not enough failures to rank the solders is denoted with a NA. Some test vehicles did not undergo certain tests which is denoted by an NT (not tested).

DRAFT July 14, 2006

Table 33 Relative Solder Performance for N10 for "Manufactured" and "Hybrid" Test Vehicles Based on Two-Parameter Weibull Analysis

Relative Solder Performance					
Component	**Solder/Finish**	**Thermal Cycle -20°C to +80°C**	**Thermal Cycle -55°C to +125°C**	**CET**	**Thermal Shock**
BGA-225	SnPb/SnPb	0	0	0	0
	SAC/SAC	P	++	--	NA
	SACB/SAC	P	++	--	NA
	SAC/SnPb	--	--	--	--
	SACB/SnPb	--	-	-	NA
CLCC-20	SnPb/SnPb	0	0	0	0
	SAC/SAC	++	--	--	--
	SACB/SACB	++	+	++	-
	SAC/SnPb	-	-	-	--
	SACB/SnPb	+	-	+	-
TQFP-144	SnPb/Sn	0	0	0	0
	SAC/Sn	P	--	-	NA
	SACB/Sn	P	++	0	NA
TSOP-50	SnPb/SnPb	0	0	0	0
	SAC/SnCu	++	--	--	NA
	SACB/SnCu	+	++	+	NA
	SAC/SnPb	+	--	-	NA
	SACB/SnPb	--	--	--	--
CSP-100	SnPb/SnPb	NT	0	0	NT
	SAC/SAC	NT	--	--	NT
	SACB/SAC	NT	--	--	NT
Hybrid-30	SnPb/SnPb	NT	0	0	NT
	SAC/SAC	NT	P	++	NT
	SACB/SACB	NT	P	++	NT

Legend:

0 = Same as control or < 5% difference	+ = 5 to 20%	++ = > 20%	- = -5 to -20%
-- > 20%	NA = Not Available	NT= Not Tested	P = Pending (awaiting data)
Red = Failure significantly more than 20% (see data for actual number)			

Table 34 Relative Solder Performance for N10 for "Rework" Test Vehicles Based on Two-Parameter Weibull Analysis

Relative Solder Performance					
Component	**Solder/Finish**	**Thermal Cycle -20°C to +80°C**	**Thermal Cycle -55°C to +125°C**	**CET**	**Thermal Shock**
BGA-225	SnPb/SnPb	NT	0	0	0
	SnPb/SAC	NT	--	--	--
CLCC-20	SnPb/SnPb	NT	0	0	0
	SnPb/SAC	NT	--	--	--
	SnPb/SACB	NT	--	-	--
TSOP-50	SnPb/SnPb	NT	0	0	0
	SnPb/SnCu	NT	-	+	-
Rwk BGA-225	Flux/SnPb	NT	0	0	0
	Flux/SAC	NT	++	0	NA
Rwk PDIP-20	SnPb/NiPdAu	NT	NA	NA	0
	SAC/NiPdAu	NT	NA	NA	NA
	SnCu/NiPdAu	NT	NA	NA	NA
Rwk TQFP-208	SnPb/NiPdAu	NT	0	0	0
	SAC/NiPdAu	NT	--	--	-- (U3)
	SACB/NiPdAu	NT	--	--	-- (U3)
Rwk TSOP-50	SnPb/SnPb	NT	0	0	0
	SAC/SnCu	NT	++	0	++
	SACB/SnCu	NT	--	--	--

Legend:

0 = Same as control or < 5% difference	+ = 5 to 20%	++ = > 20%	- = -5 to -20%
-- > 20%	NA = Not Available	NT= Not Tested	P = Pending (awaiting data)
Rwk = Reworked component	Red = Failure significantly more than 20% (see data for actual number)		
U3 = Data was only available for component location U3, TQFP-208 component			

7 Conclusions

7.1 Assembly Conclusions

1. Assembly of high-performance electronics using Pb-free solder alloys is possible without a total retrofit of the modern factory. Some control of equipment may be necessary where concern for contamination from a previous SnPb process exists, such as the wave solder pot.
2. Higher processing temperatures impact the soldering process window (e.g., dwell times, flux chemistry), component moisture sensitivity controls, and solder flux residue removal.
3. Significant resources will be required for component configuration management to assure that incompatible metallurgies are not mixed in the factory. The huge potential for mixed components from suppliers will drive validation and inspection costs throughout the factory.

7.2 Reliability Conclusions

1. Results from individual tests (combined environments, thermal cycling and vibration testing) should not be used alone to make definitive decisions on Pb-free reliability. Results from this study should be taken as a whole.
2. Component type has the greatest effect on solder joint reliability performance (greater than does solder alloy) for thermal cycling and combined environments. The plated through-hole components are more reliable than the surface mount technology components for thermal cycling and combined environments.
3. Component location on the board has a significant effect on solder joint reliability performance for vibration.
4. Mixed solder BGA-225s failed early for thermal shock.
5. The results of this study suggest that for some component types and environments, Pb-free solders are as reliable as the currently used eutectic SnPb solder. Unfortunately, this study also demonstrates that with other component types and environments, the Pb-free solders fail before the SnPb control.
6. For many components SACB solder joints were at least as reliable as the SnPb controls during the combined environments and thermal cycling tests. (Exceptions were when SACB was contaminated with SnPb.)
7. The SAC soldered components were at least as reliable as the SnPb soldered controls for -20^{o}C to + 80^{o}C thermal cycling. However, SAC soldered components were often less reliable than the SnPb soldered controls during -55^{o}C to +125^{o}C thermal cycling, vibration and combined environments.
8. Under high-stress conditions, SnPb generally outperforms Pb-free. For low stress conditions, Pb-free generally outperforms SnPb.
9. “Manufactured” (High T_g) SnPb solder joints outlasted “Rework” (Low Tg) SnPb solder joints during thermal cycling and combined environments testing. Therefore, PWB

laminate characteristics (i.e., CTE and modulus) can be expected to affect the lifetime of Pb-free soldered hardware. For this study, one should exercise caution when comparing data from the “Manufactured” (High Tg) boards and the “Rework” (Low Tg) boards.

10. The impact of SnPb contamination on the Pb-free solder alloy reliability is mixed. For SAC, SnPb contamination can increase or decrease reliability. For SACB solder alloy, SnPb contamination usually has a detrimental effect on reliability. The degree of degradation of SACB solder joint reliability appears to be inversely proportional to the amount of SnPb contamination in the solder joint. Therefore, soldering with SACB solder requires appropriate factory management to eliminate lead contamination.
11. Combined Environments Testing holds promise for replacing long term thermal cycling to accelerate the testing of future Pb-free solder alloys for some designs, especially if the general results and conclusions are similar to other tests.

8 Recommendations

1. The lower reliability of the Pb-free solder joints shown in some tests does not necessarily rule out the use of Pb-free solder alloy on aerospace and defense electronics in some use environments. However, models for calculating the actual field lifetime of Pb-free solder joints on certain component types must be developed and validated using actual test data (from this and other studies). These models can then be used to verify that electronics made with Pb-free solders will survive for the required lifetime in their use environments.
2. The next logical step is system-level demonstration/validation of promising Pb-free solders on functional Class 3 aerospace and defense electronic systems. This will also help validate entire Pb-free assemblies in an operational environment.
3. The tests in this study evaluated only solder joint reliability. Therefore, additional testing must be done to determine the effect of higher reflow temperatures on printed wiring boards and functional integrated circuits.
4. Pb contamination must be better understood and controlled if SACB solder is to be utilized. The level of control of Pb contamination required when soldering with SACB may not be available to service centers and might pose an unacceptable risk to high-performance systems. If Pb contamination is not controllable, that may preclude the use of SACB solder on some or all aerospace and defense electronics.
5. The results of this study should be used with other industry data as part of a comprehensive data set when considering Pb-free solder process implementation.